Science and Technology Facilities Council

ISIS Neutron and Muon Source

Neutron detectors and applications at spallation sources: from meV to GeV

Years of ISIS Neutron and Muon Source

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31st January 2025

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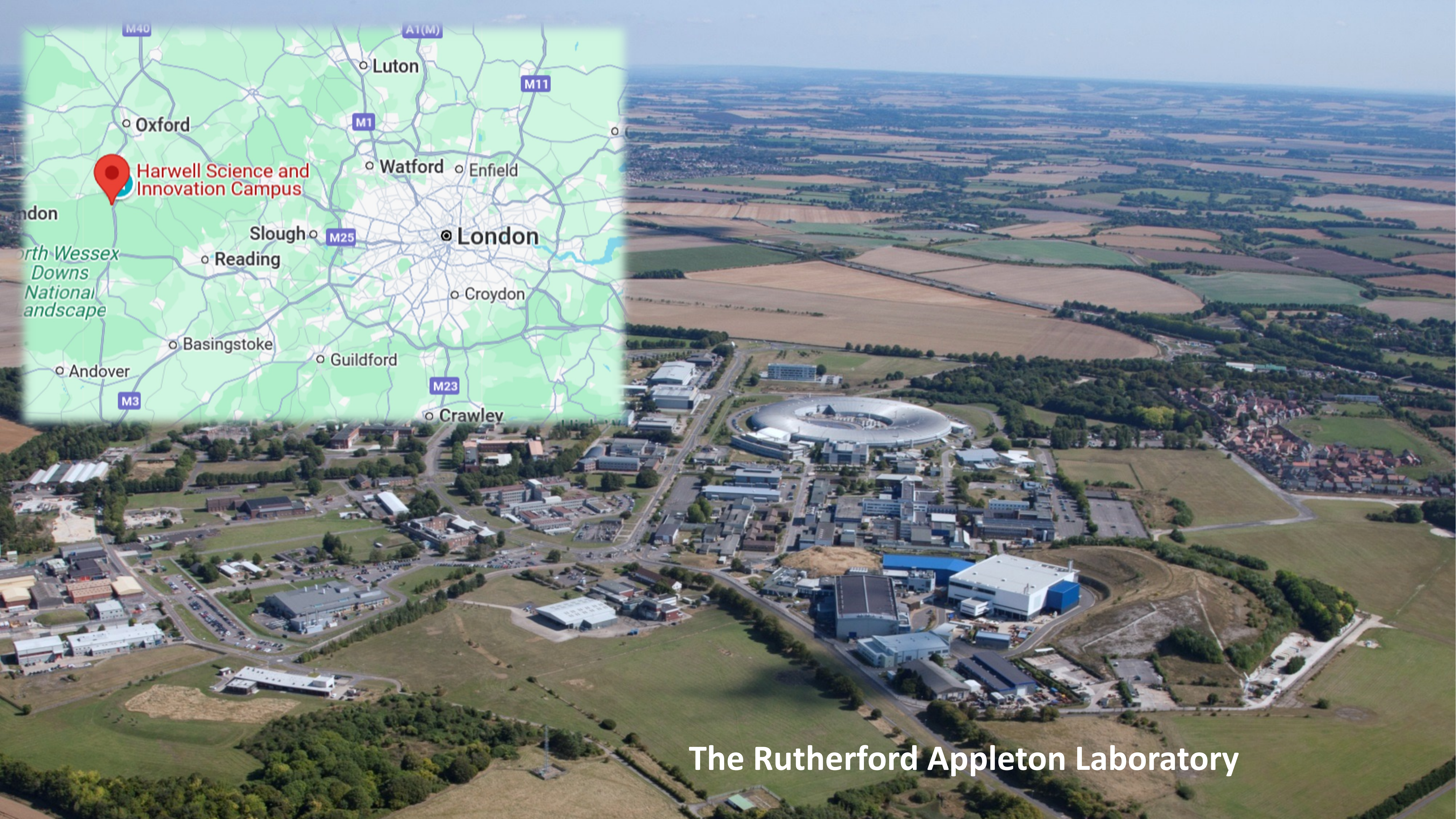


The Rutherford Appleton Laboratory

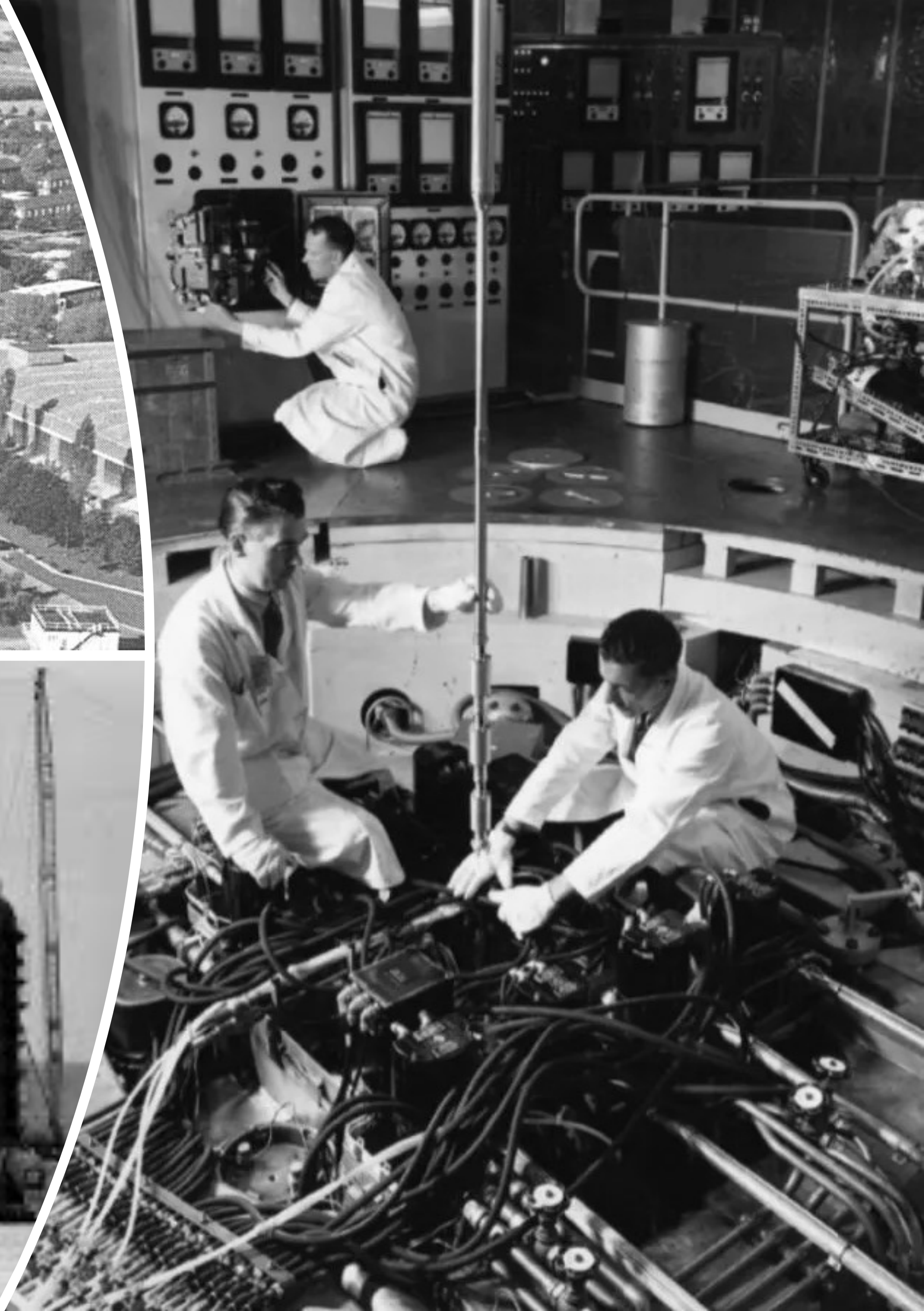
RAF Harwell – Est. 1935

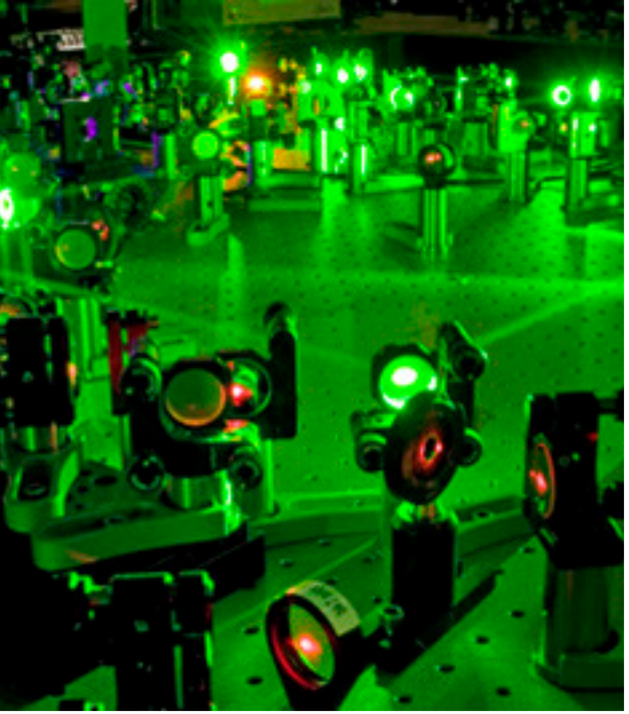
- Defending Britain during the battle of London
- D-day 6 June 1944 – Troops of British 6th Airborne Division

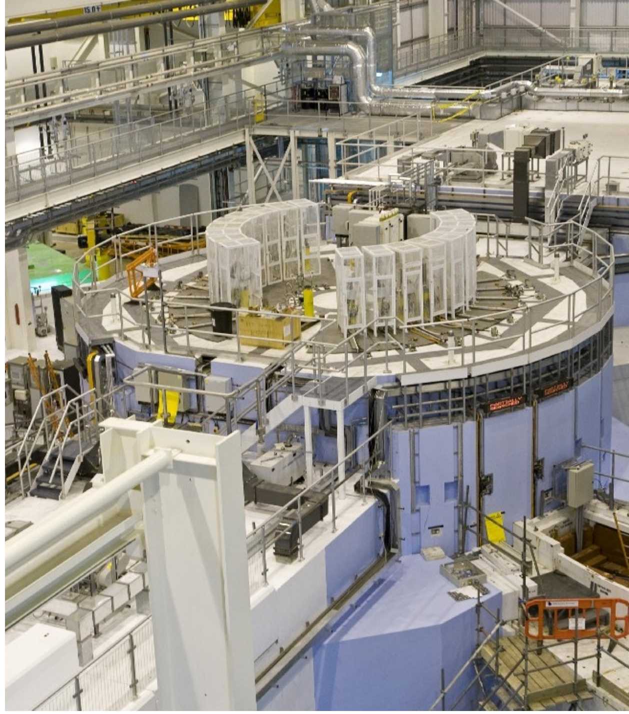
UKAEA
est.1946

- Main research establishment of the United Kingdom Atomic Energy Authority
- 1947: GLEEP test reactor generates nuclear energy for the first time in western Europe
- You can still see the decommissioned DIDO and PLUTO reactors







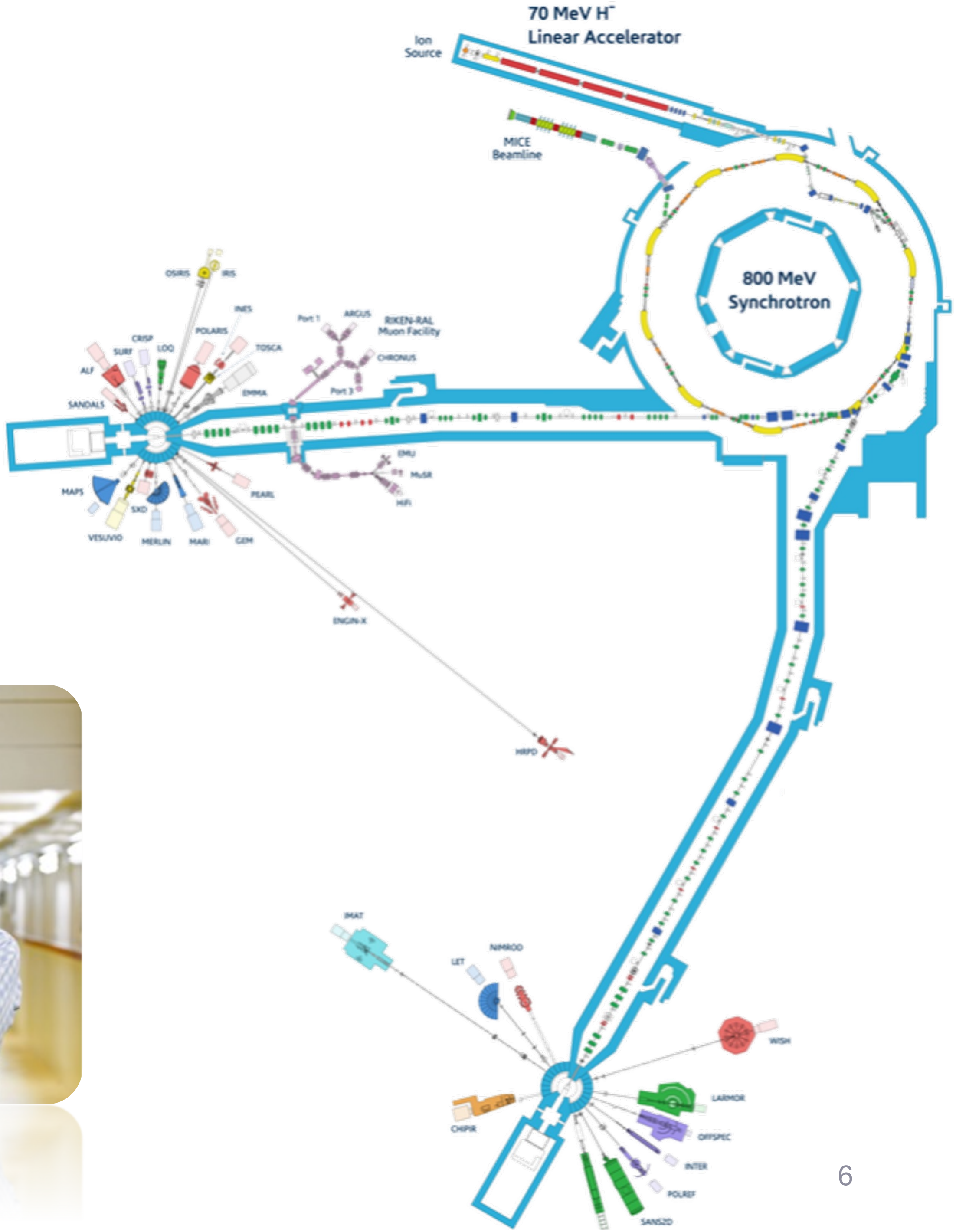




Rutherford Appleton Laboratory

- One of the national scientific research laboratories in the UK operated by the Science and Technology Facilities Council (STFC)
- The site hosts some of the UK's major scientific facilities

The ISIS neutron source

- 70 MeV Linac
- 800 MeV proton syncrotorn
- Two extraction lines
- Protons on tungsten targets
- Two target stations with moderators
- 30 neutron beamlines, 8 muon beamlines



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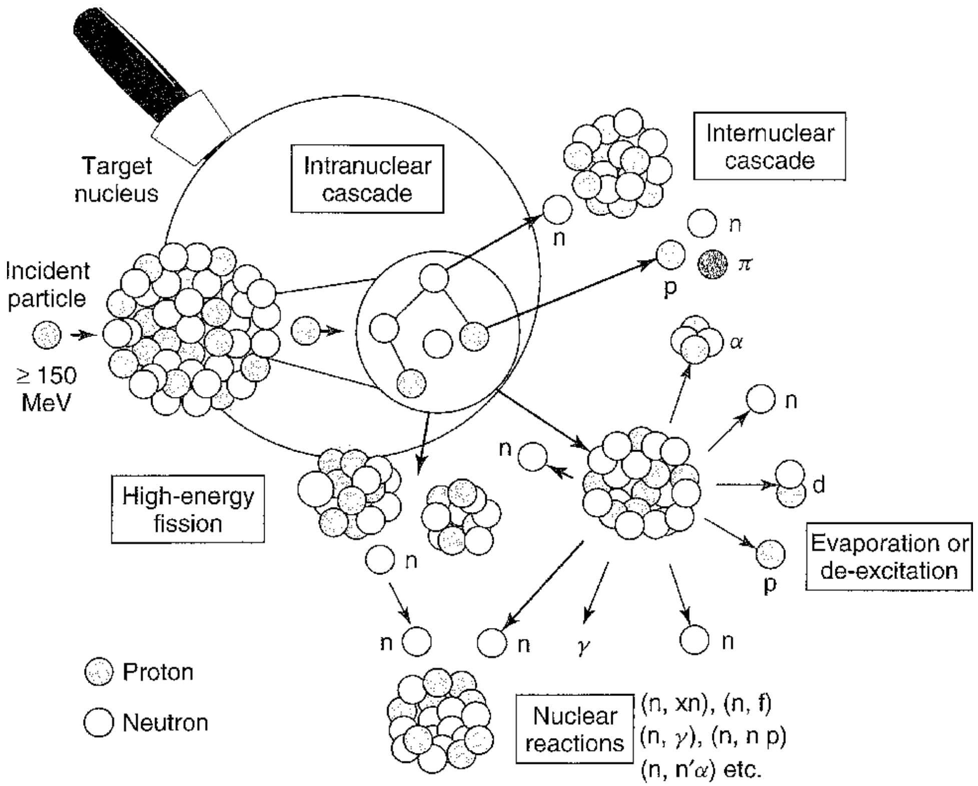
ISIS Neutron and Muon Source
@isisneutronmuon

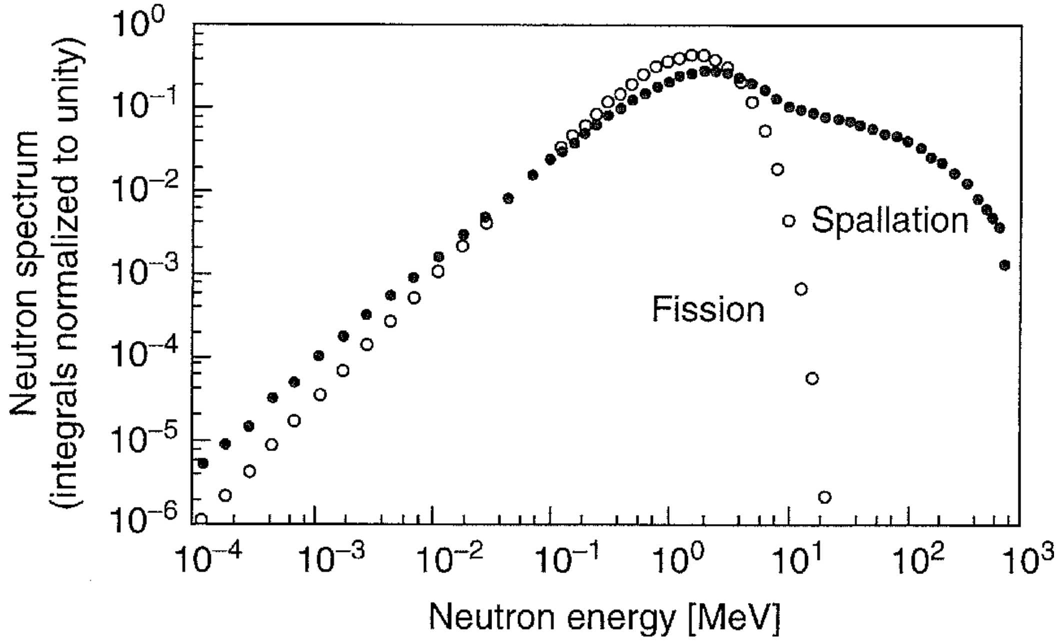
It was #OnThisDay in 1984 that first neutrons were produced at ISIS!
#HappyBirthday to us 🥳

40 Years of ISIS Neutron and Muon Source

UKRI Science and Technology Facilities Council

Spallation neutron production





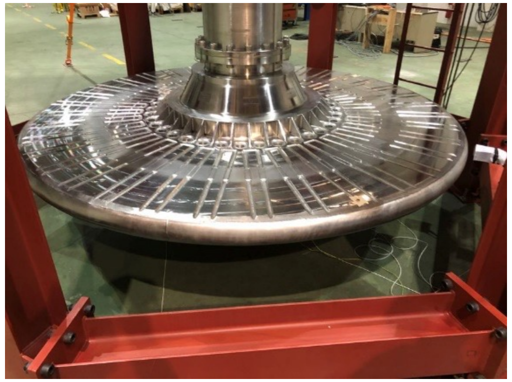
Target materials

Tungsten
ISIS (UK), LANSCE (USA), CSNS (China), ESS (Sweden)

Liquid Mercury
SNS (USA), J-PARC (Japan)

Lead
PSI (CH), nToF (CERN)

ISIS TS2



ESS

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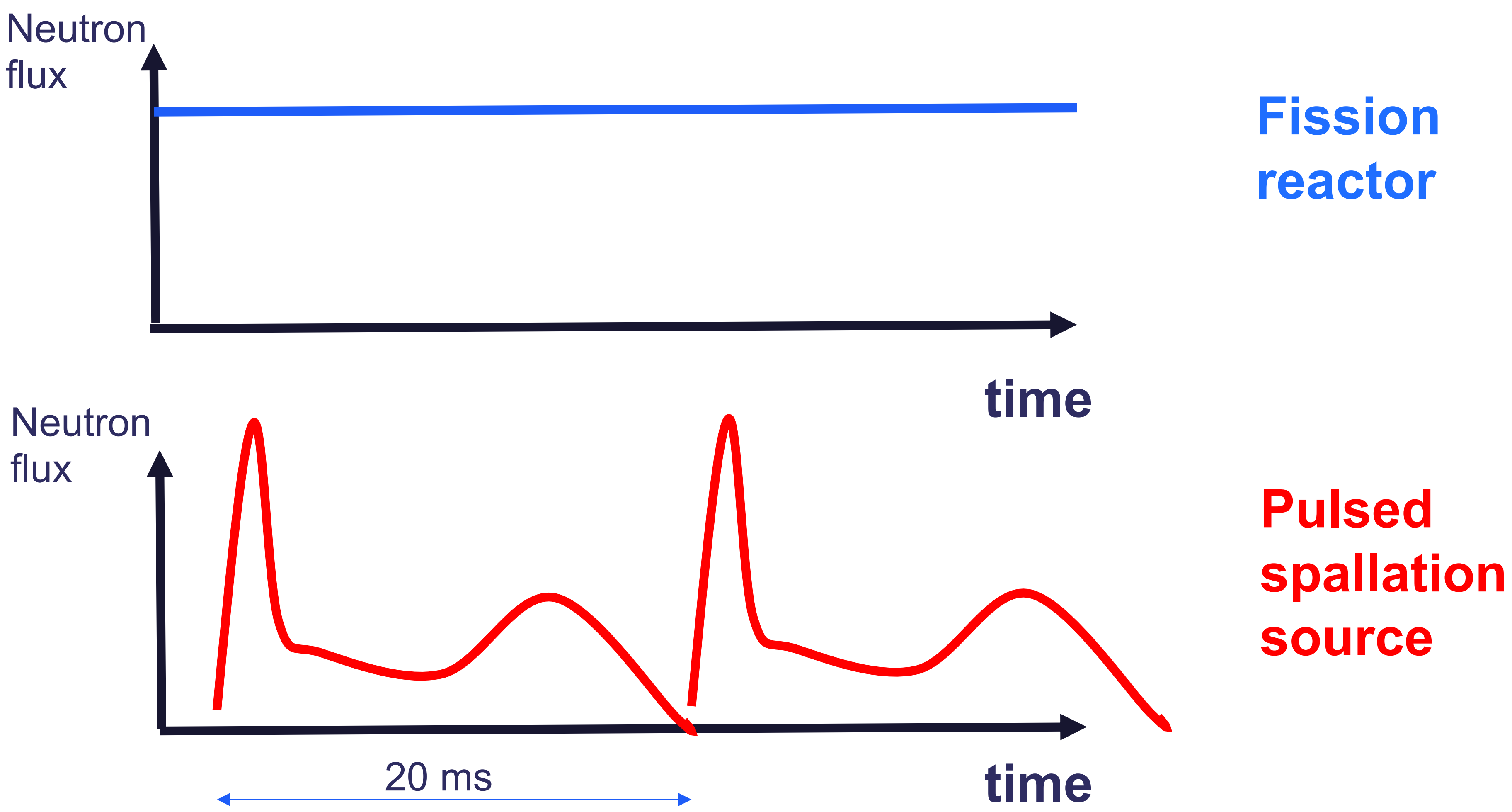
Pulsed neutron production



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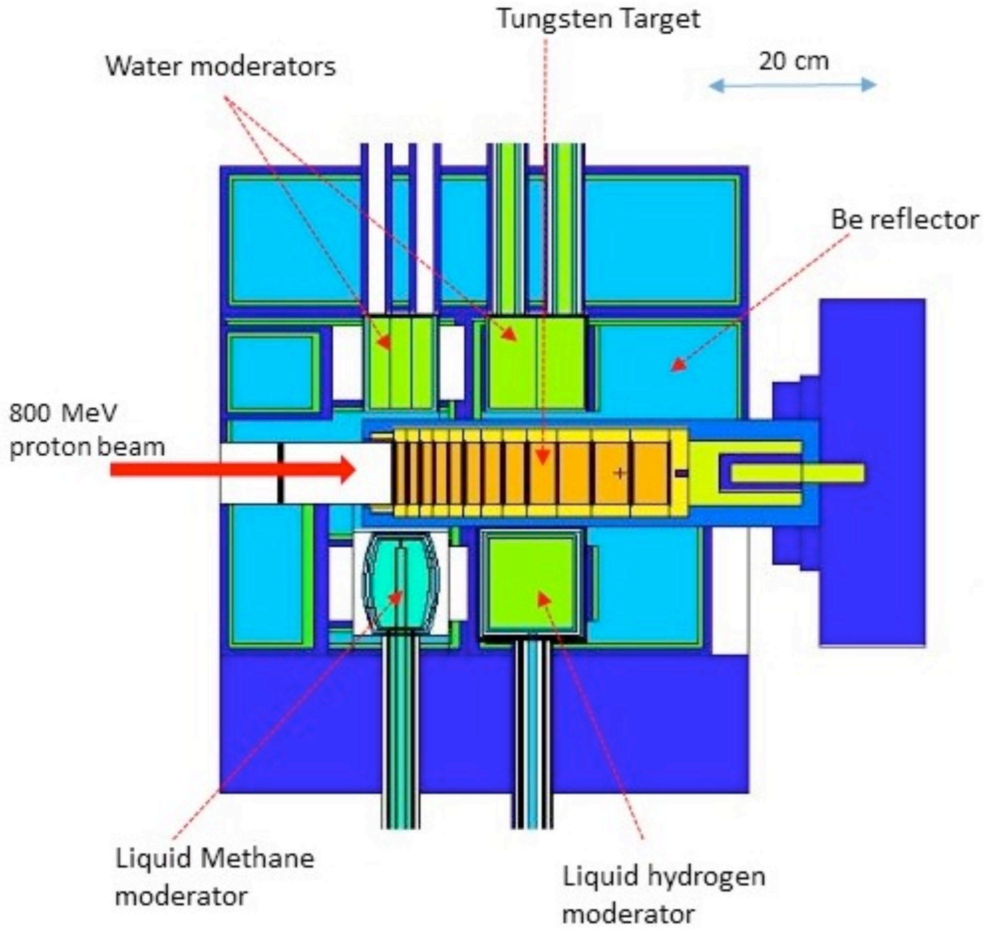
Neutron moderation



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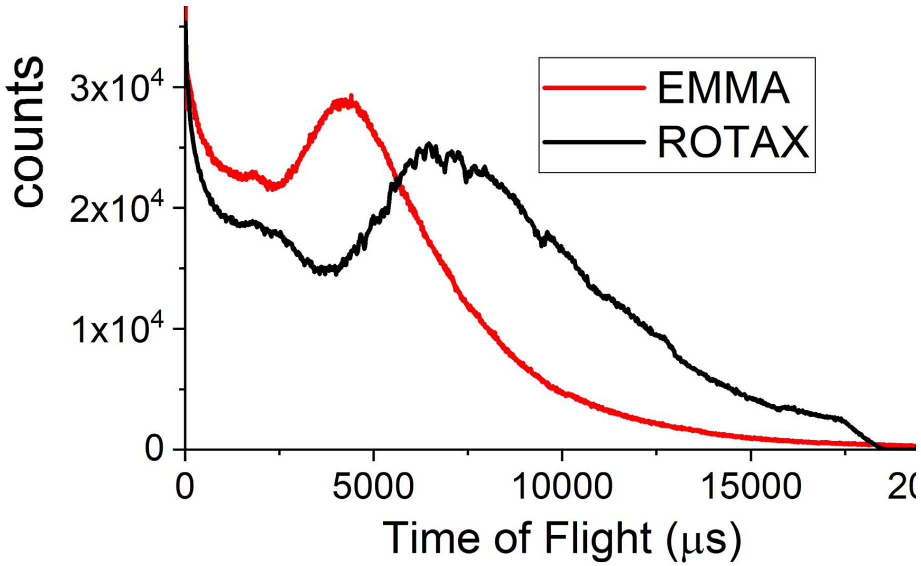
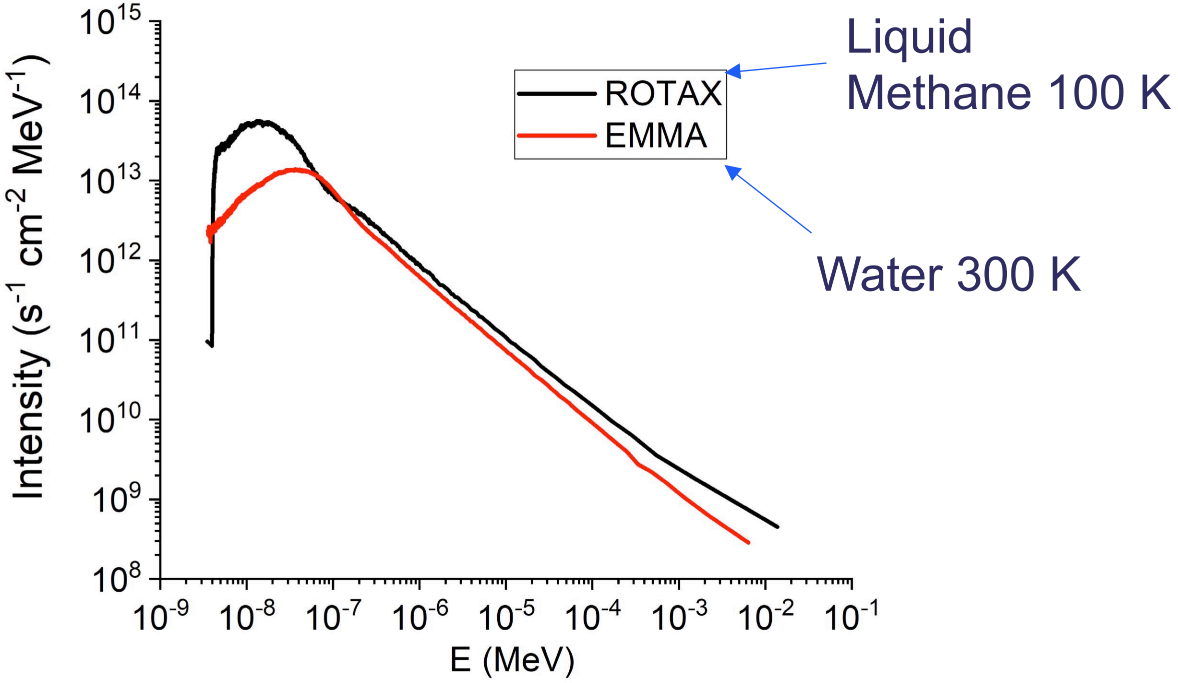
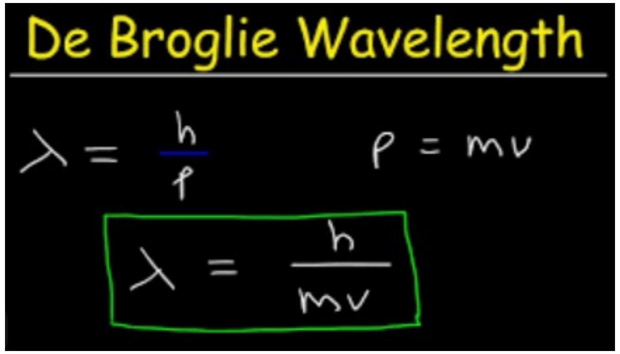
Neutron moderation

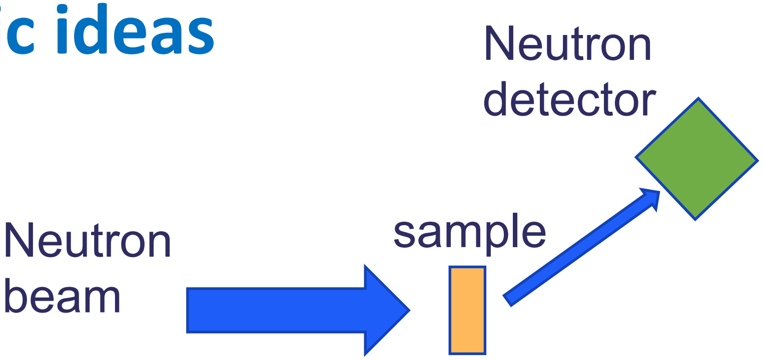
$$E = \frac{1}{2}m\left(\frac{L}{\mathrm{ToF}}\right)^2$$

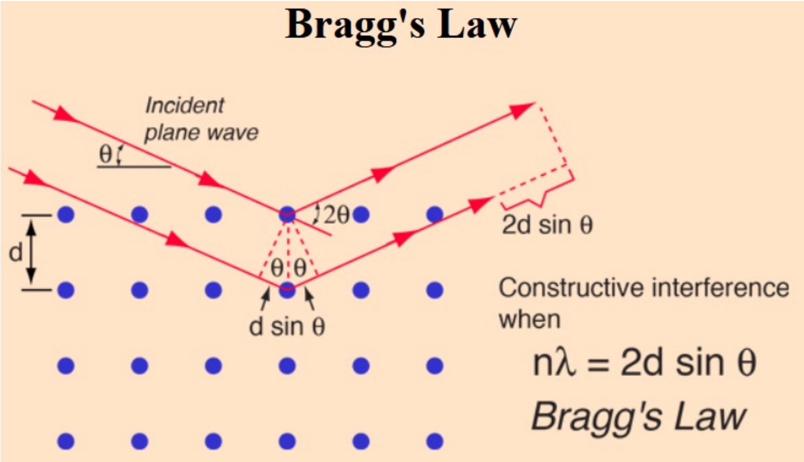




Neutron diffractions: basic ideas







X-ray diffraction

$\lambda \approx 1.5$ Å → $E = h\nu = 8.2$ keV

Neutron diffraction

$\lambda = h/mv \approx 1$ Å → $E = 25$ meV

What can be measured

- Scattering angle
- Exchanged energy
- Change in magnetic momentum

Important points:

- Neutron energies are small -> **thermal neutrons**
- Neutron are very penetrating -> **bulk materials**
- Neutron energies are comparable to energies of **vibrations in solids and liquids**. -> dynamics.
- Neutron cross sections are sensitive to **light elements**, like hydrogen, where x-rays ar not sensitive

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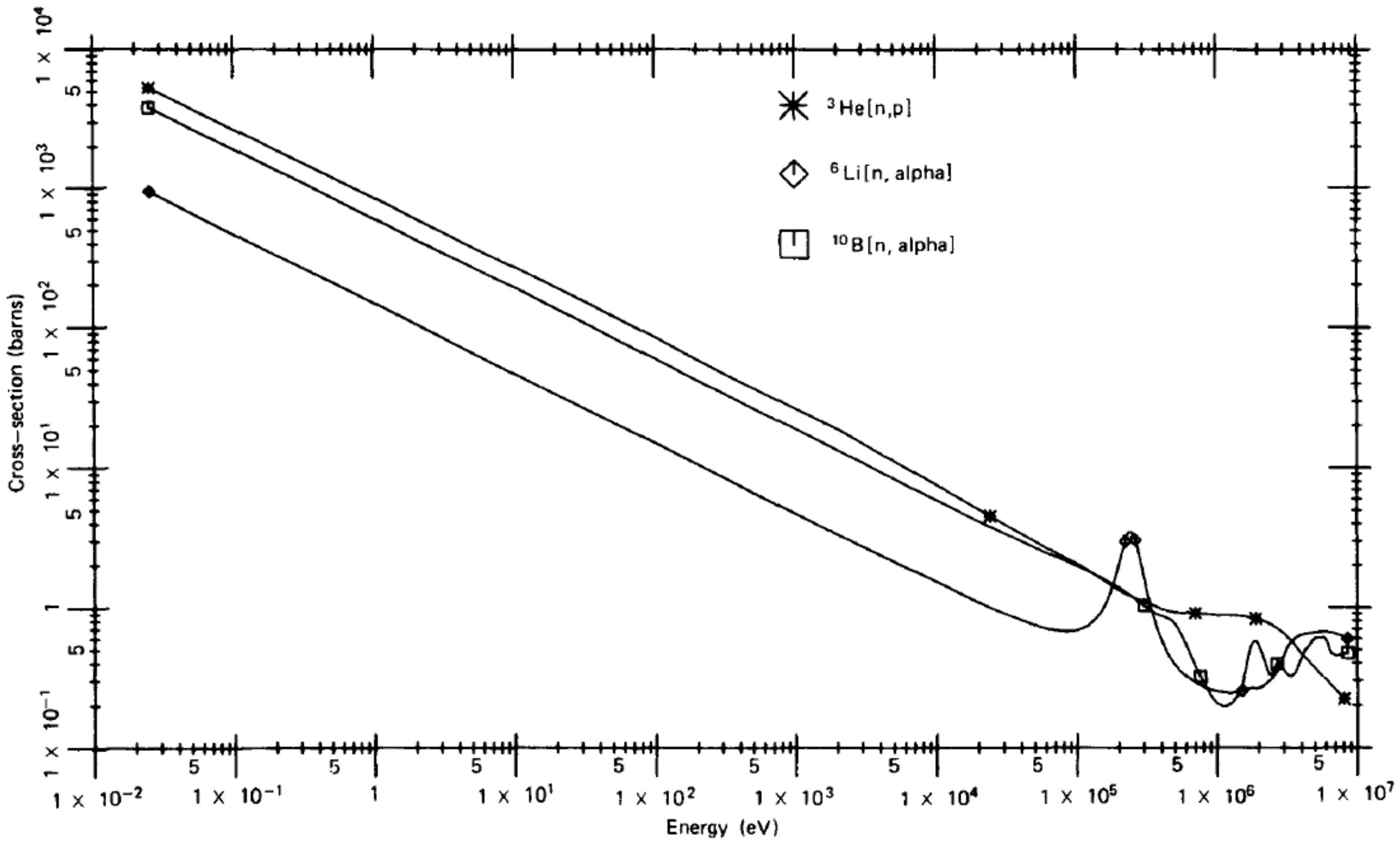
Thermal neutron detection

Cross sections for thermal neutrons

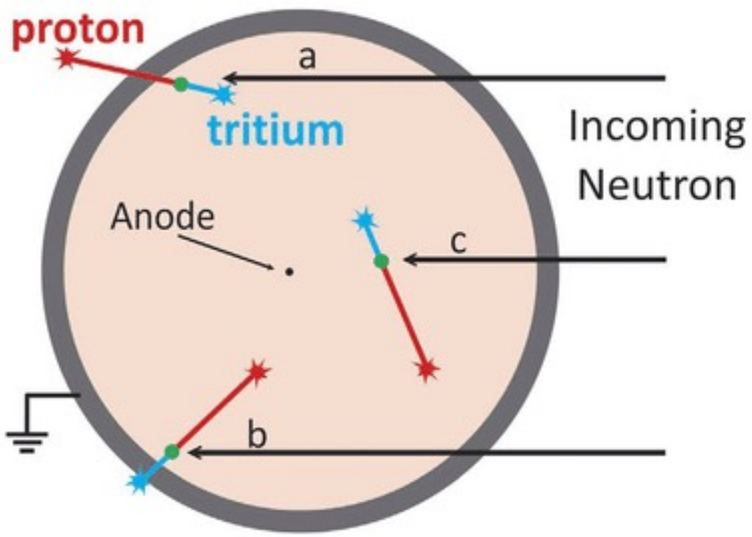
- $^{3}He \rightarrow 5330$ b
- $^{10}B \rightarrow 3848$ b
- $^{6}Li \rightarrow 940$ b

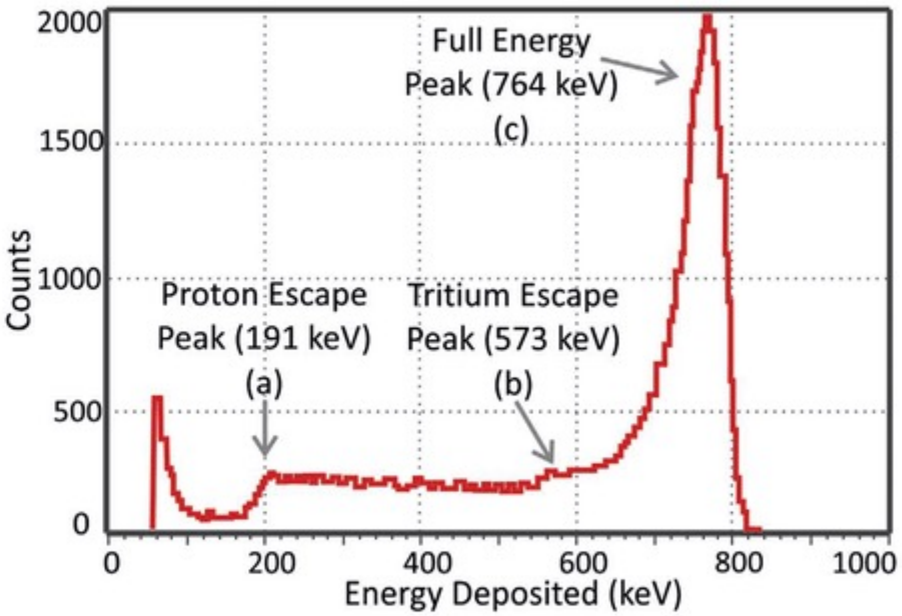


^{3}He tubes

$$^{3}\mathrm{He} + \mathrm{n} = {}^{3}\mathrm{H} + \mathrm{p} \quad \text{Q-value}=0.764\ \text{MeV}$$

- Very high efficiency > 50%
- Position sensitive
- Very established technique
- Shortage of 3He
- High price
- Limited count rate





^{3}He data

Natural abundance	0.000137% (% He on Earth) 0.001% (% He in Solar System)
Half-life ($t_{1/2}$)	stable

Virtually all helium-3 used in industry today is produced from the radioactive decay of tritium, given its very low natural abundance and its very high cost.

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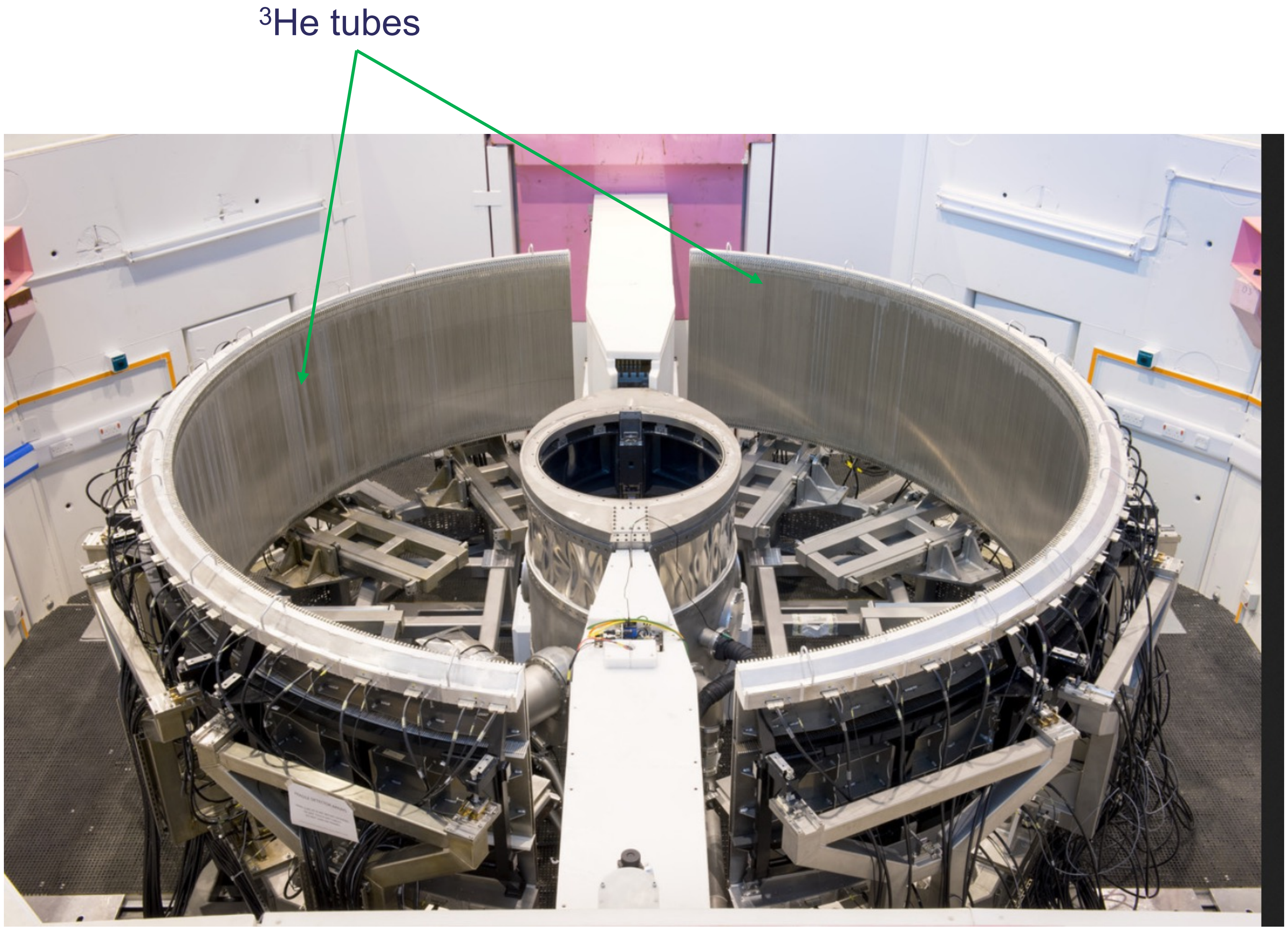
Use example: WISH

WISH is a long-wavelength diffractometer primarily designed for powder diffraction at long d-spacing in magnetic and large unit-cell systems. The instrument is also suitable for measuring single-crystals.



How does data look like?

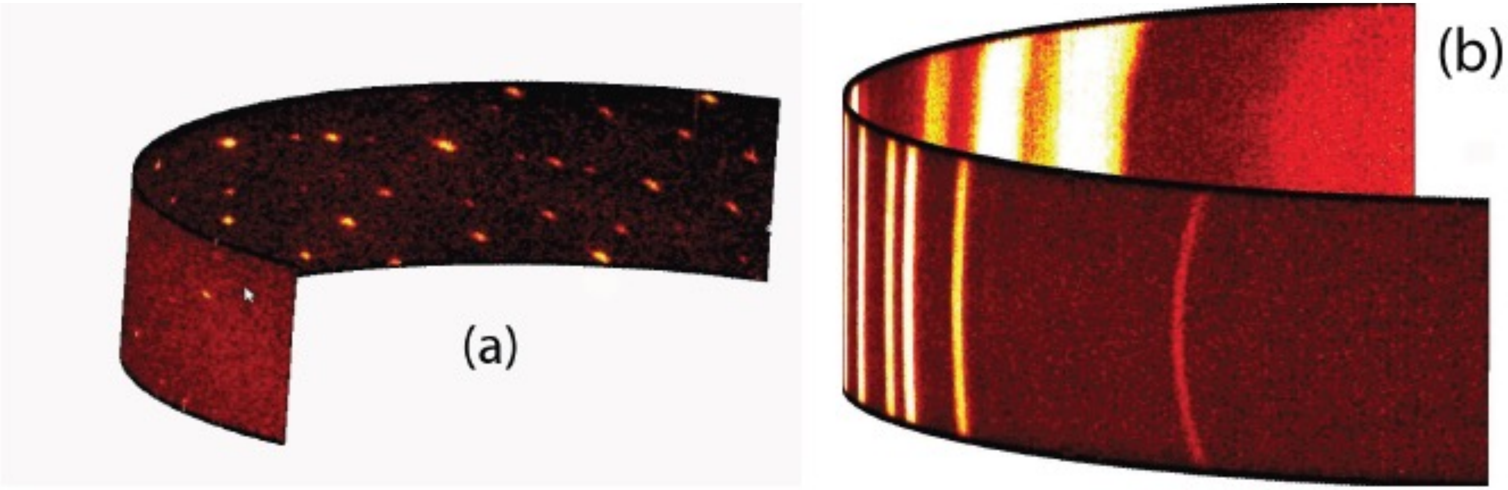
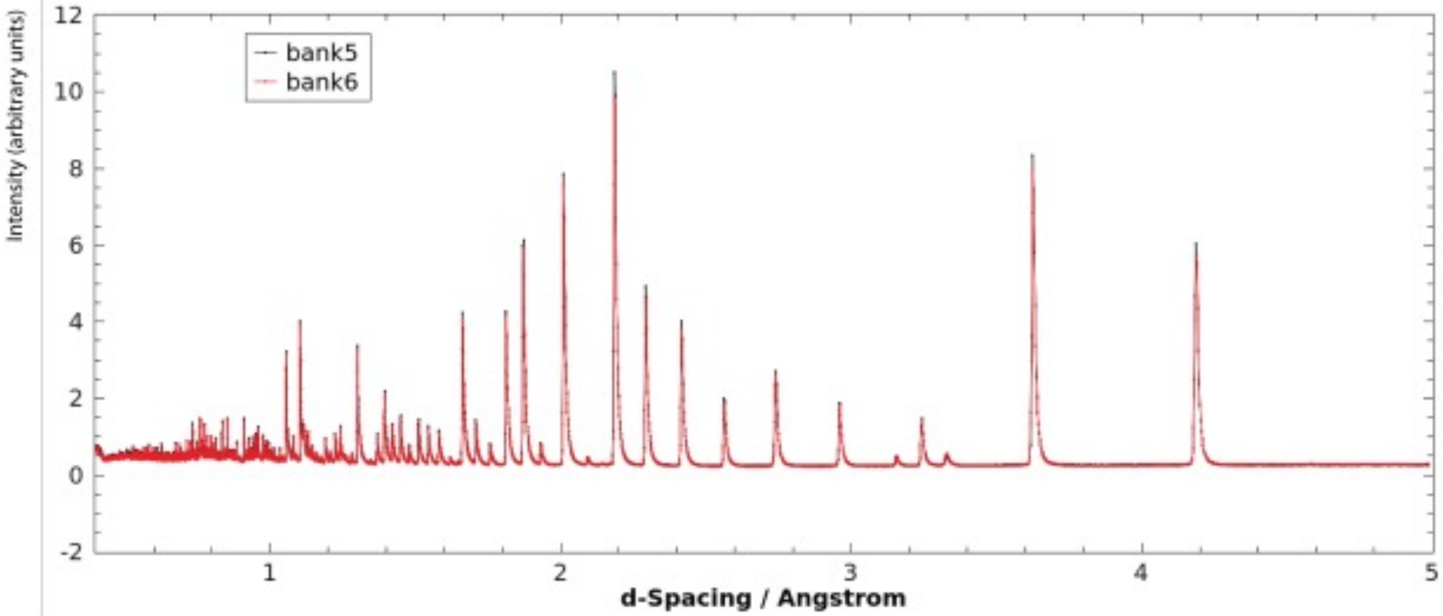


Figure 8. Diffraction data sets obtained from (a) single crystal of $BaMnF_4$ and from (b) silicon powder.



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Scintillation detectors based on ZnS/^{6}LiF

Compared to ^{3}He

Pro:

1. Availability

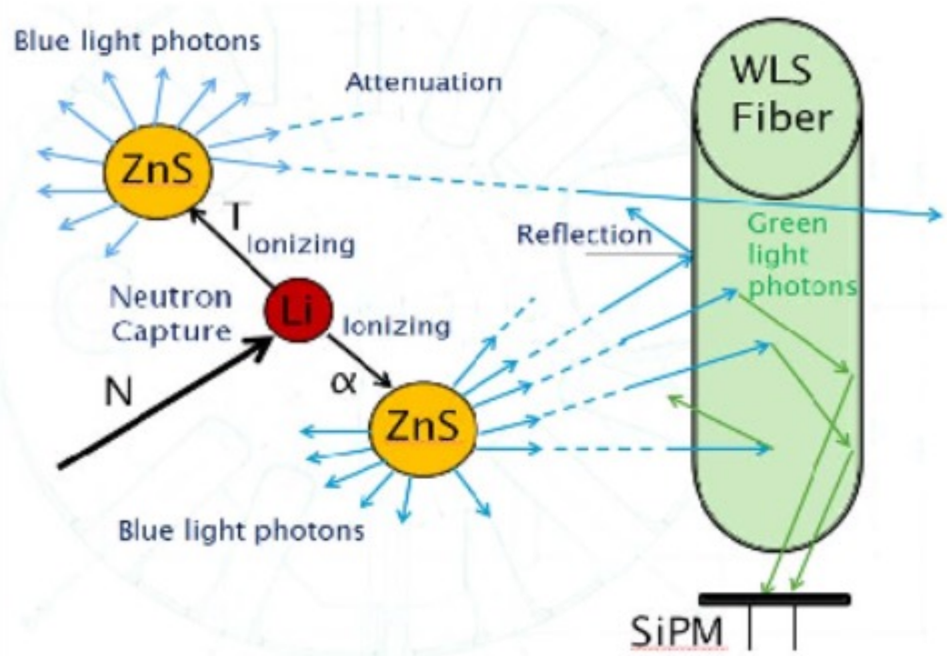
2. Scalability: larger sizes.

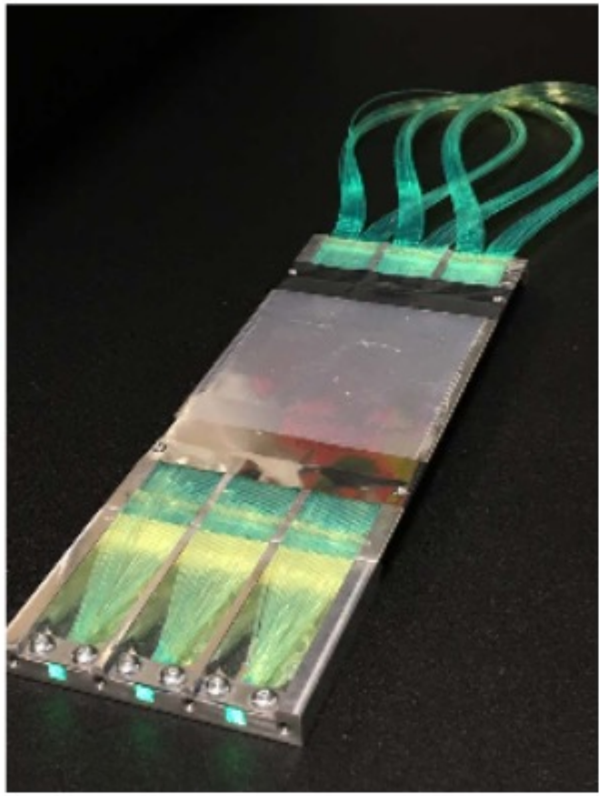
3.Versatility in Design.

4.Better spatial resolution

Con:

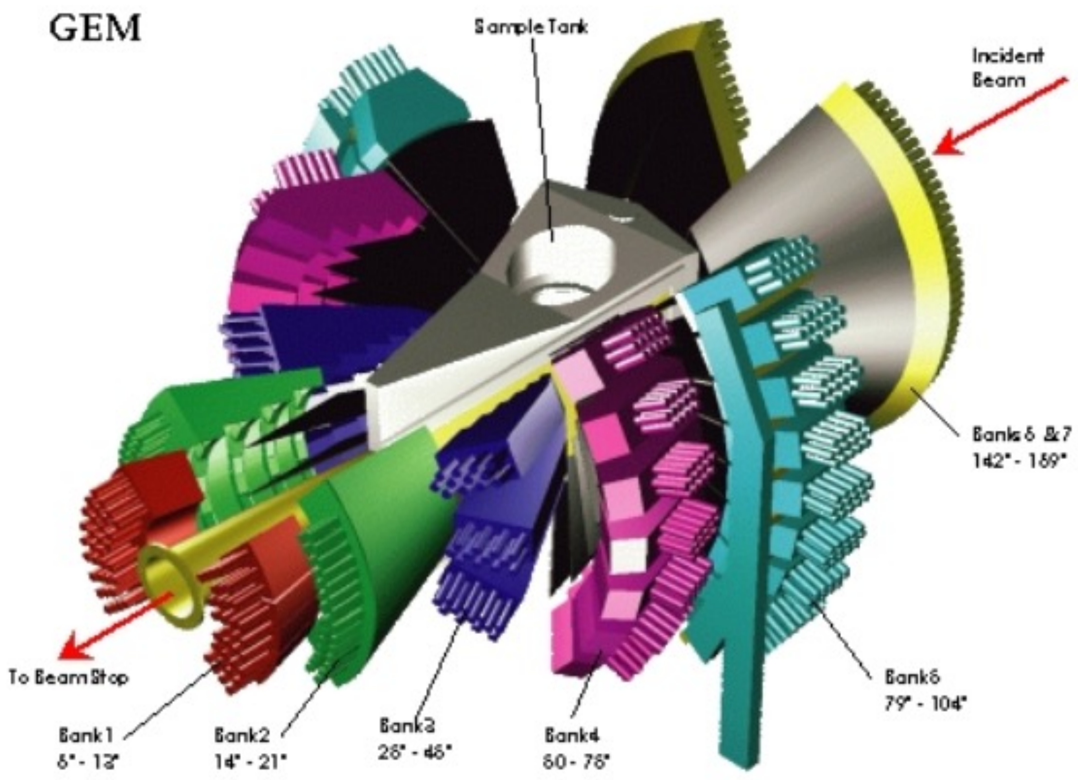
1. Lower efficiency than ^{3}He
2. Higher gamma background

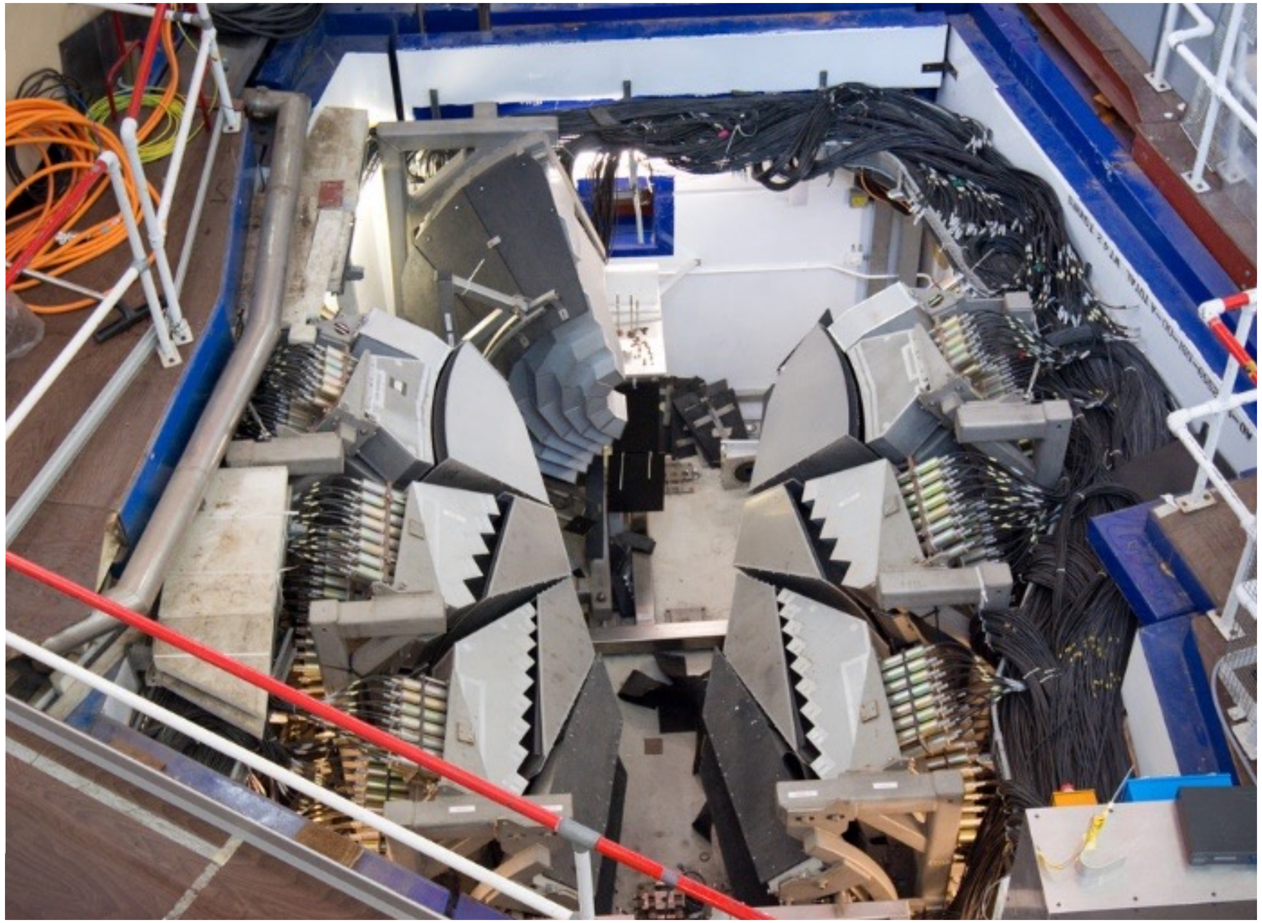




Use example: GEM

General Materials Diffractometer





the GEM scintillator detector system contains 660,000 individual optic fibres, whose total length will be about 350 kilometres.

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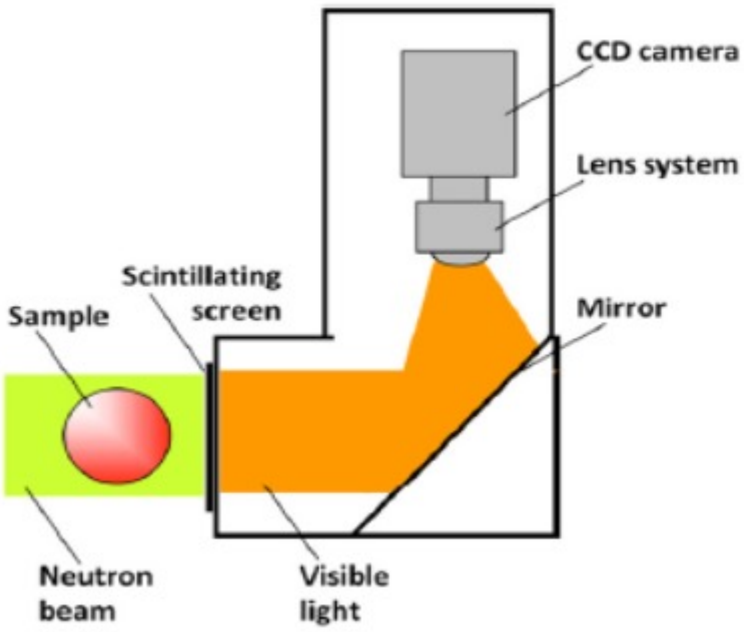
Neutron imaging detectors

Screen + CCD



Screen ZnS/^{6}LiF

B doped microchannel plates

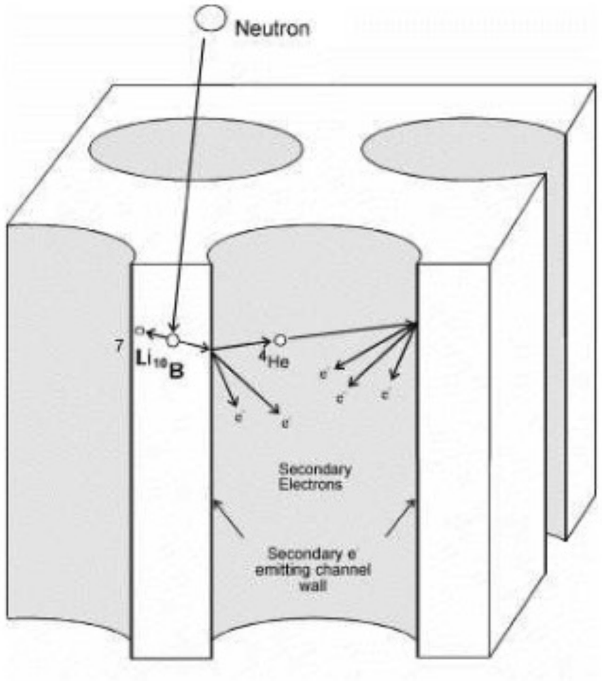
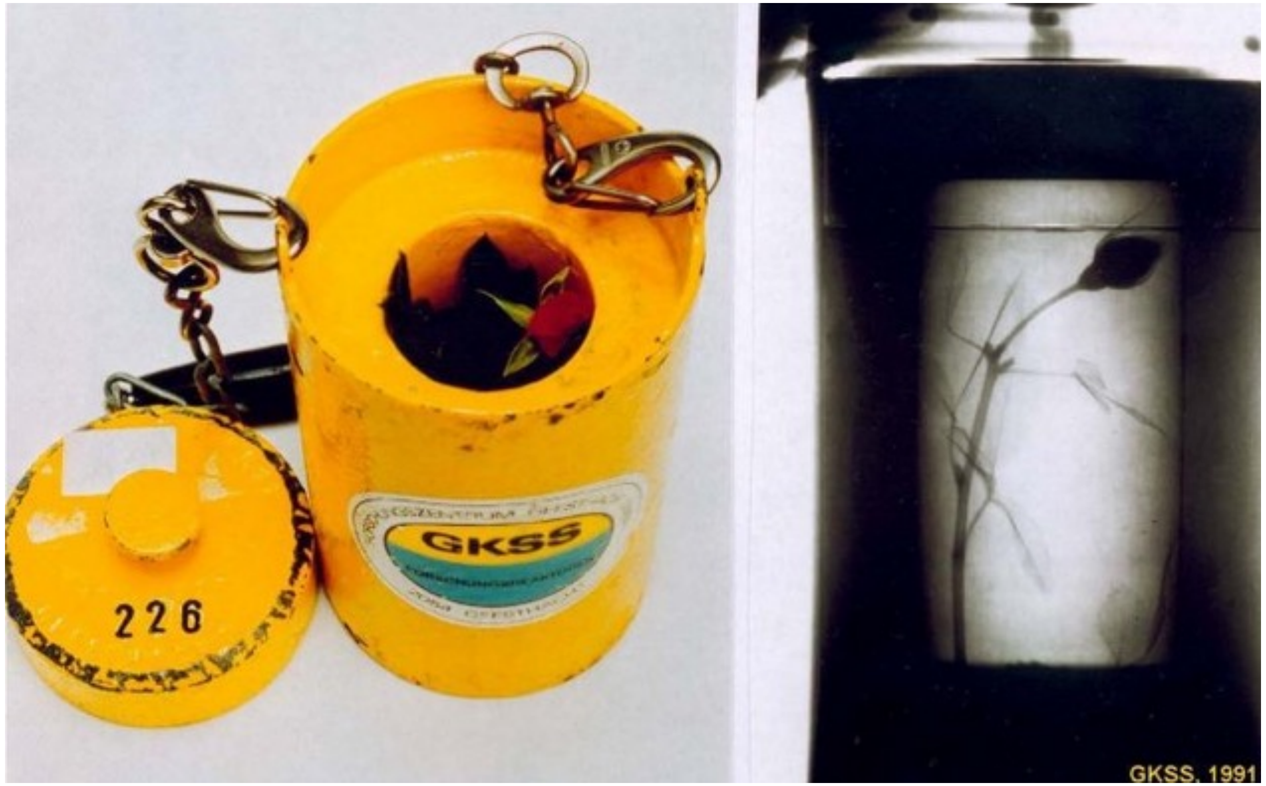
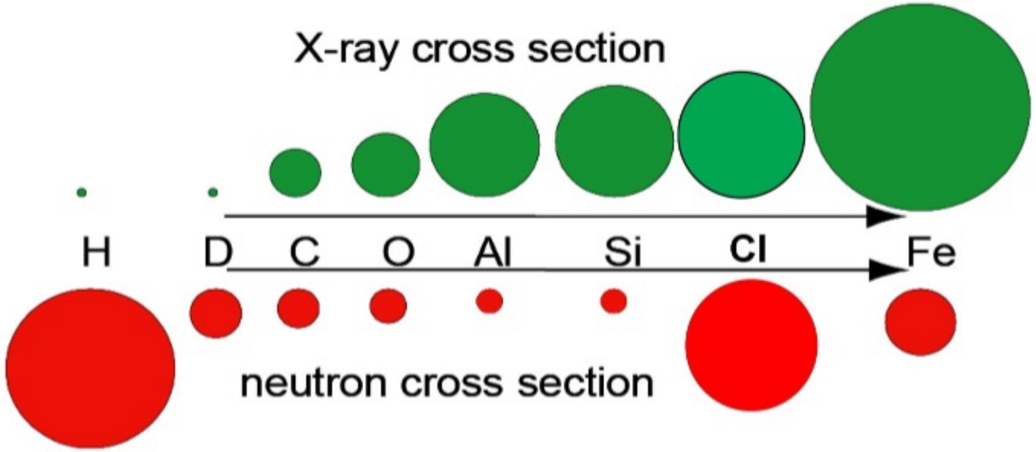


Fig. 2: Detection mechanism of the MCP-based detectors [19].

Neutron imaging

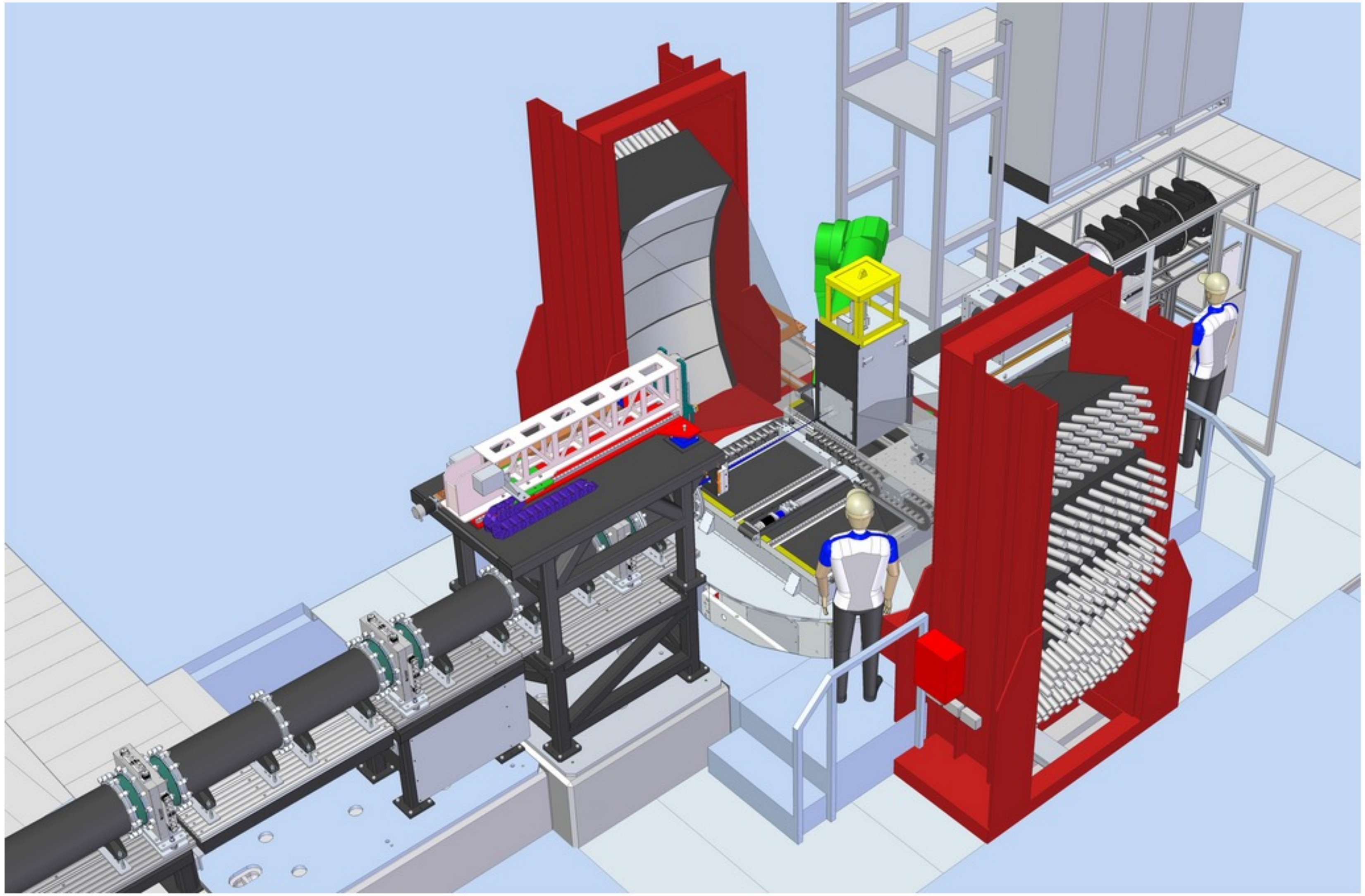




Important points

- Contrast of low Z materials
- At spallation sources can be combined with diffraction

Example: IMAT



IMAT schematic with tomography camera and 90-degree diffraction detectors

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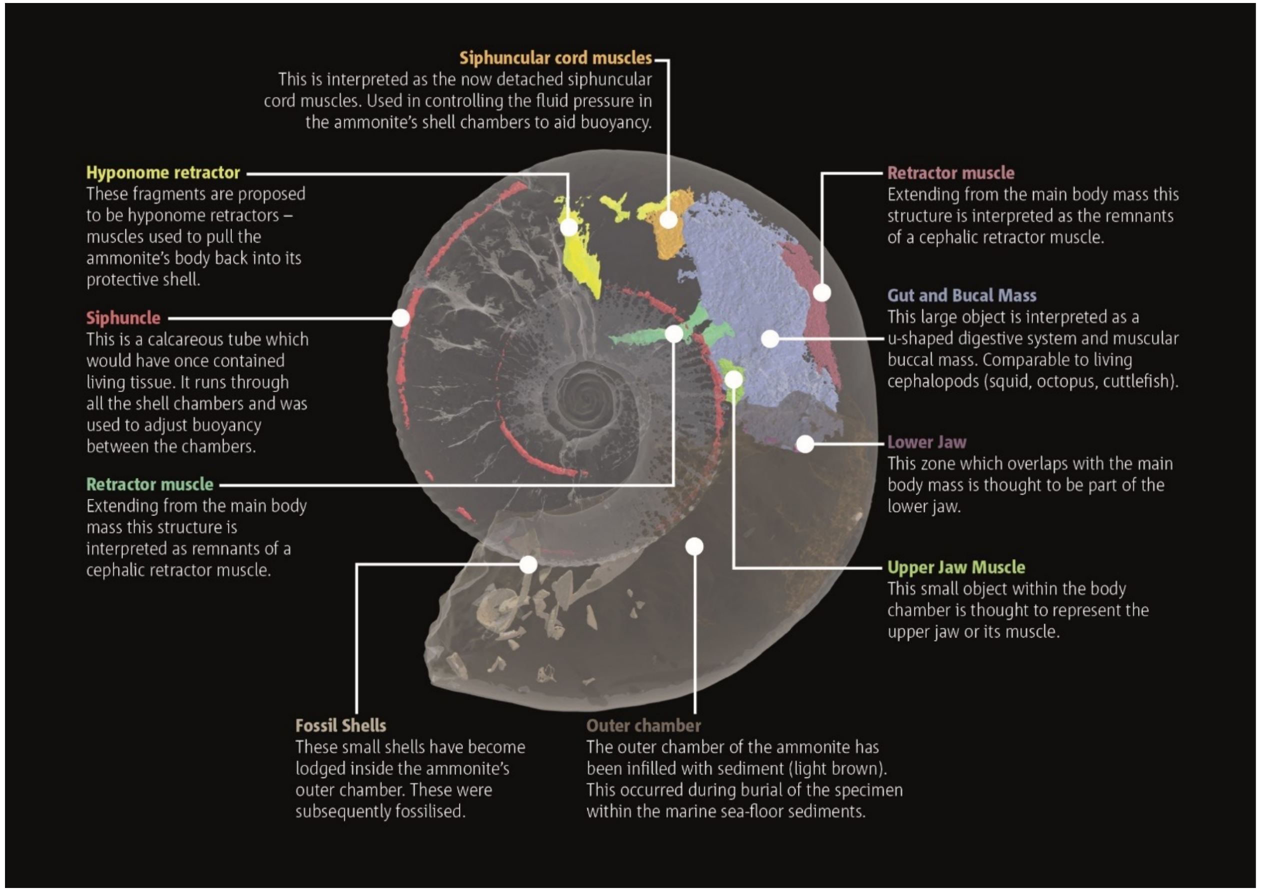

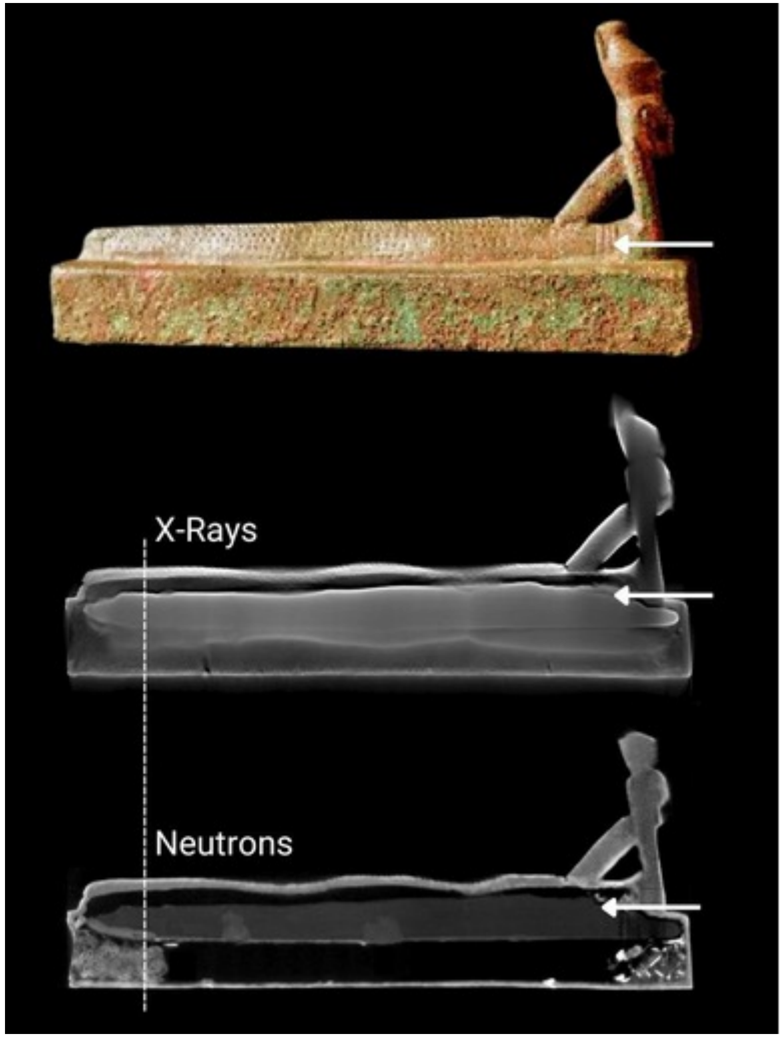

"Zombie Lizards"

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Other Boron-based neutron detectors: GEM detect

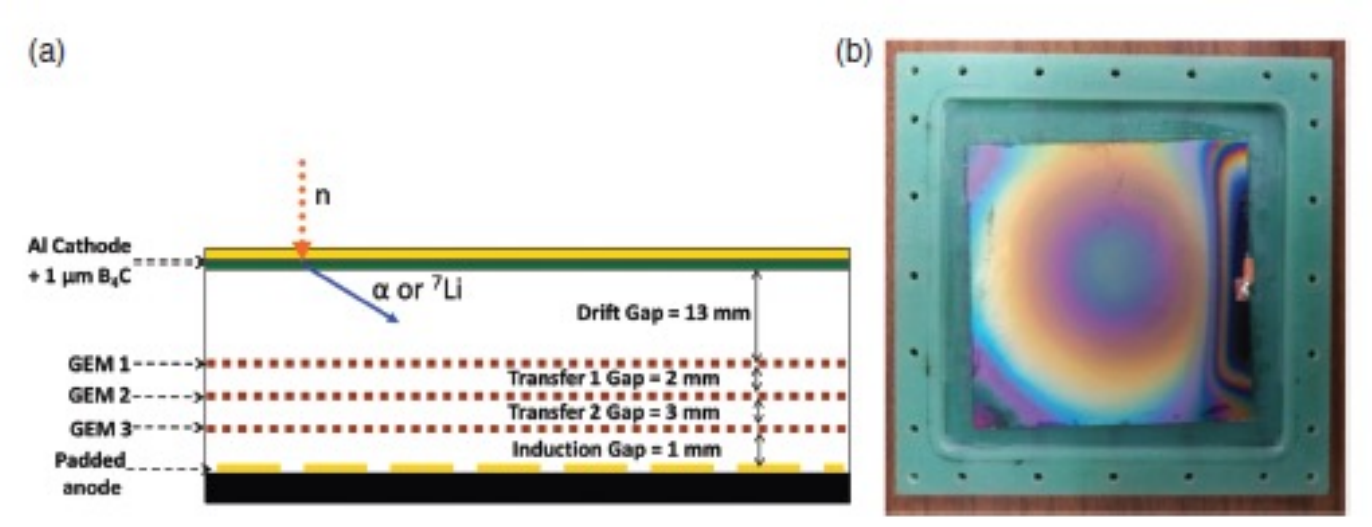
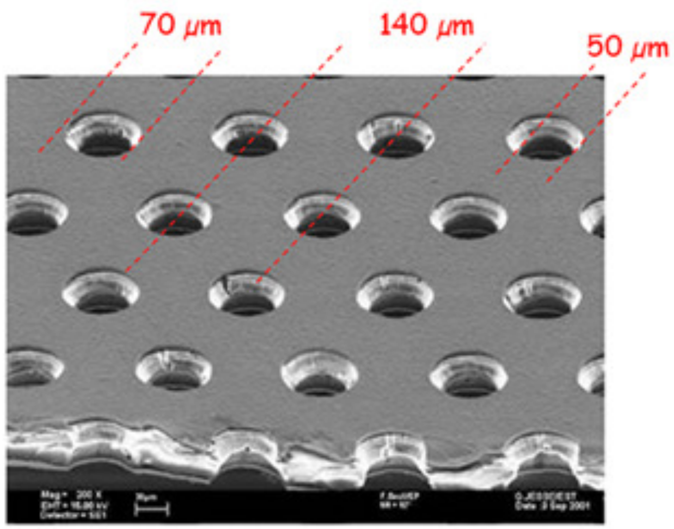
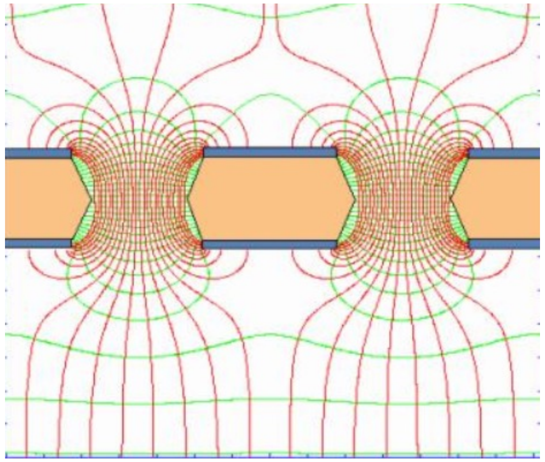


Fig. 2. (a) Detector schematics; (b) borated cathode.





Pro:

- Very high counting rate capabilities
- Low sensitivity to gamma
- Large areas are possible

Con:

- Low efficiency for a single layer, need a more complex multi-layer approach

High fluxes: Very good for in-beam measurements or Small Angle instruments

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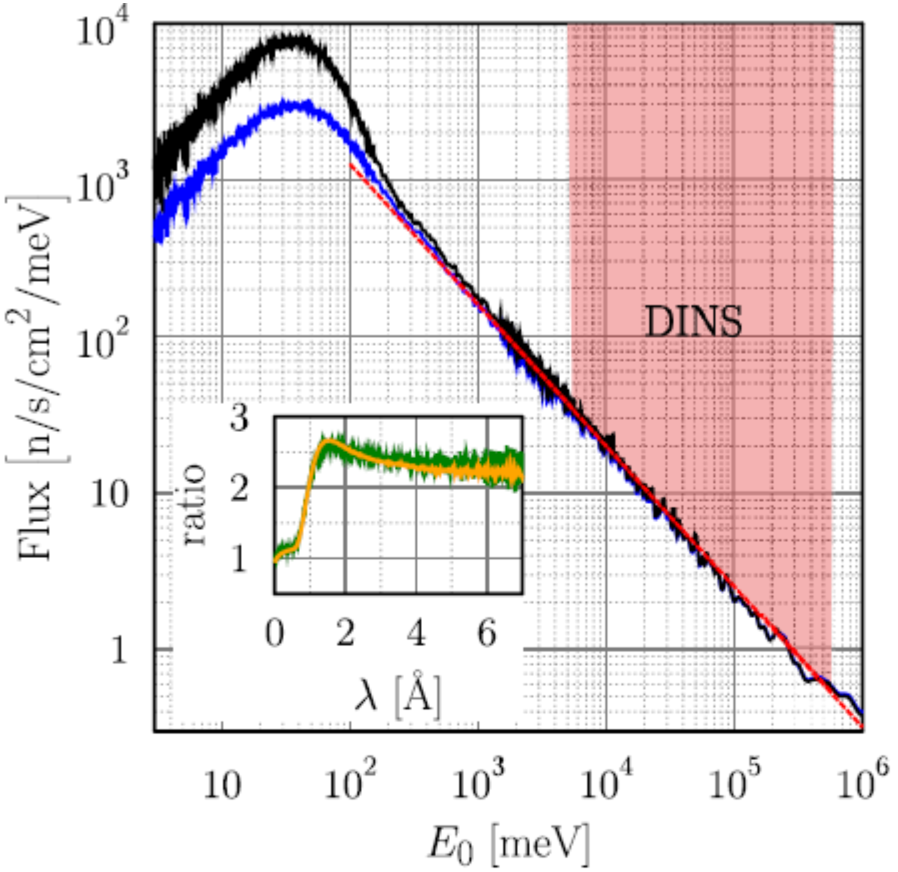
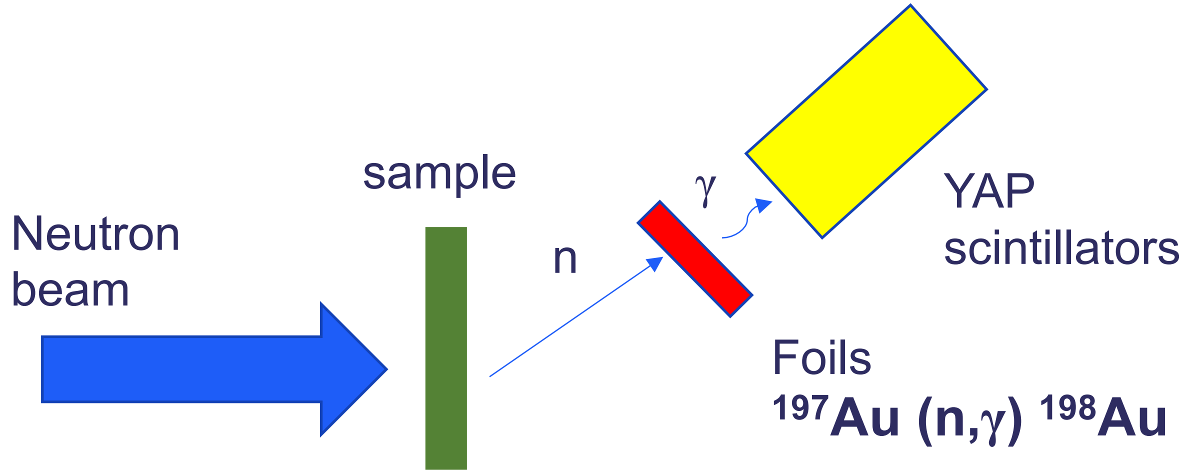
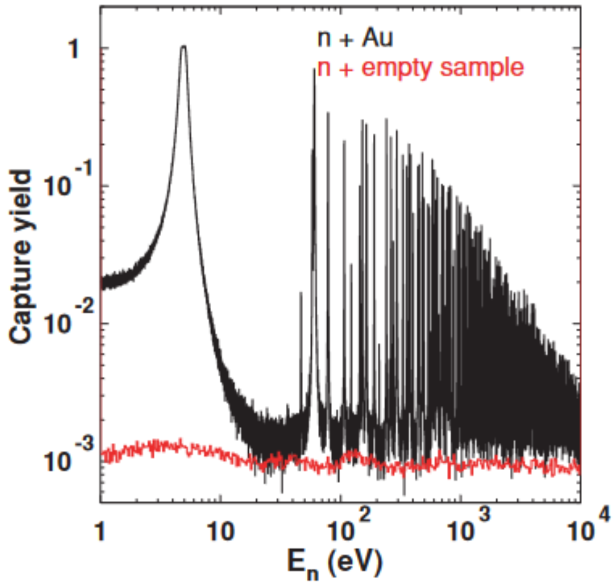
VESUVIO
Epithermal neutrons: eV to keV

DINS = Deep Inelastic Neutron Scattering







Incoming energy known with ToF

Resonances of a gold foil

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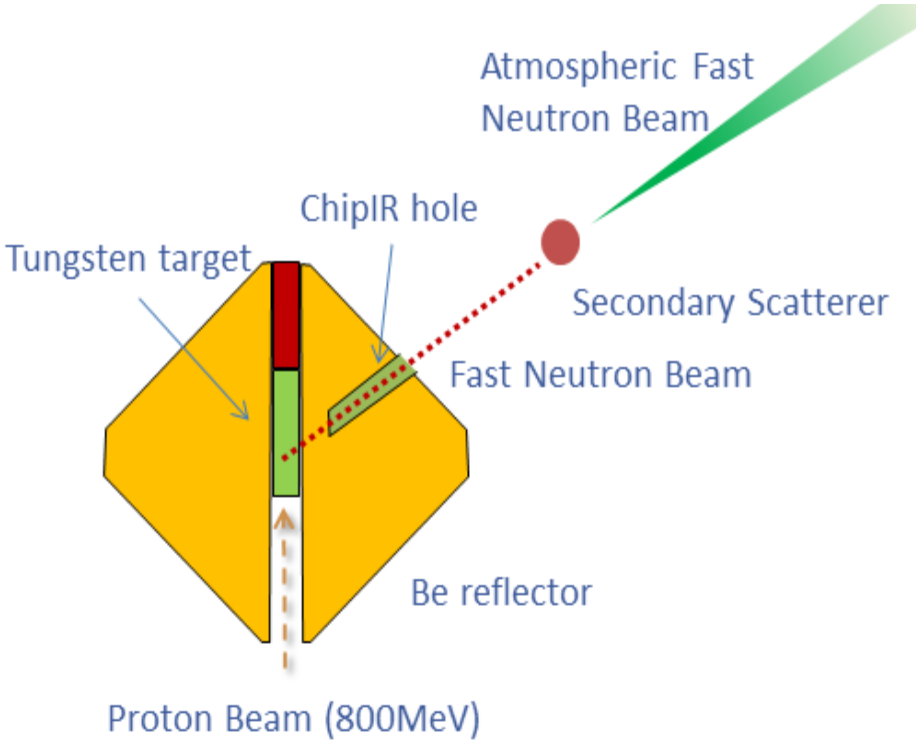
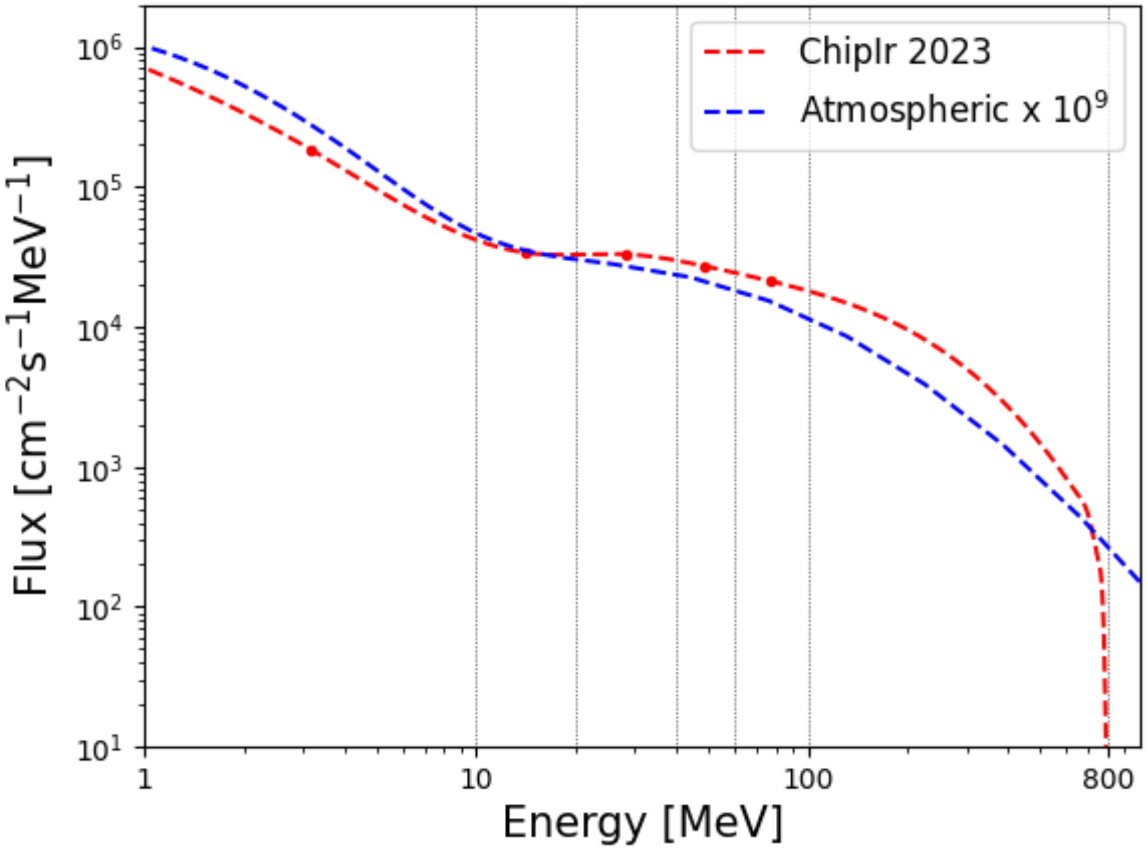
The main goal of experiments on VESUVIO is the measurement of atomic momentum distributions and nuclear quantum effects in condensed matter systems.

ChipIR: fast neutrons E >10 MeV





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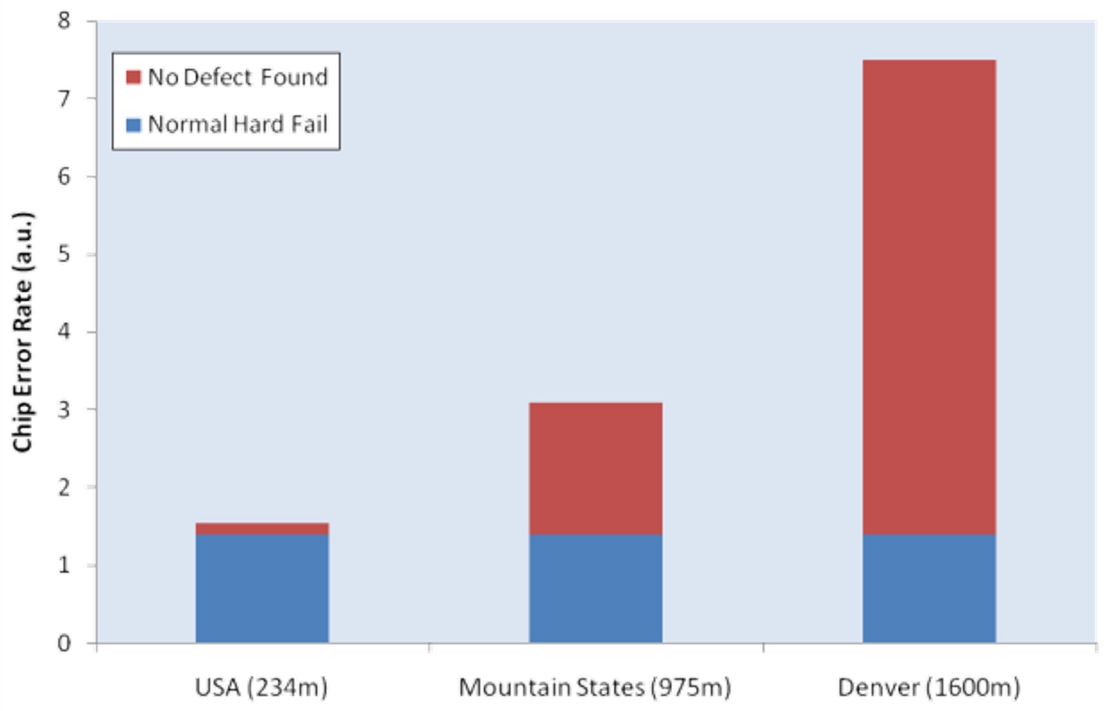
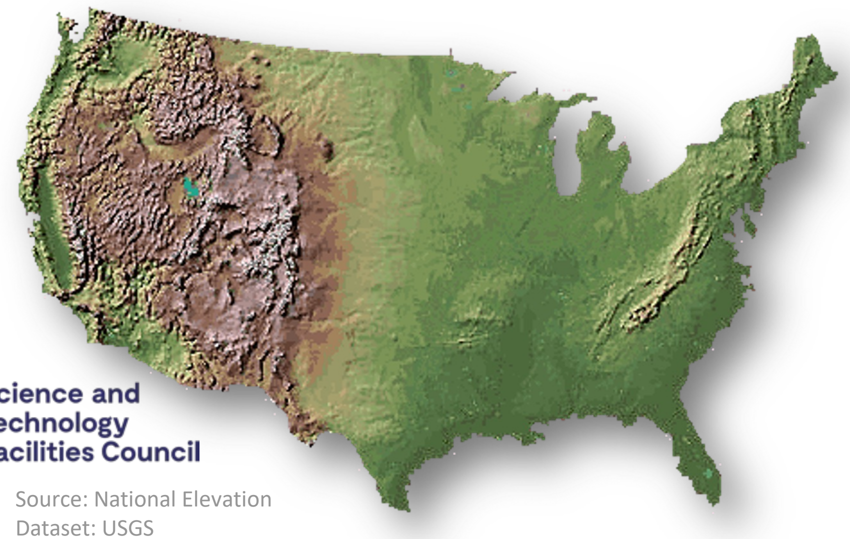
ChipIr Flux (>10 MeV) = 5.8 x 10^6 n $cm^{-2}s^{-1}$



Reproduced from J.F.Ziegler et al IBM. J. Res. Develop. 40, 1996, p3



Source: National Elevation Dataset: USGS

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‘Real-world Incident’

7th October 2008 at 04:40:26
Flight Qantus QF72
Singapore to Perth

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Equivalent of 3 Blackpool Rollercoasters

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ATSB TRANSPORT SAFETY REPORT Aviation Occurrence Investigation
AO-2008-070
Final

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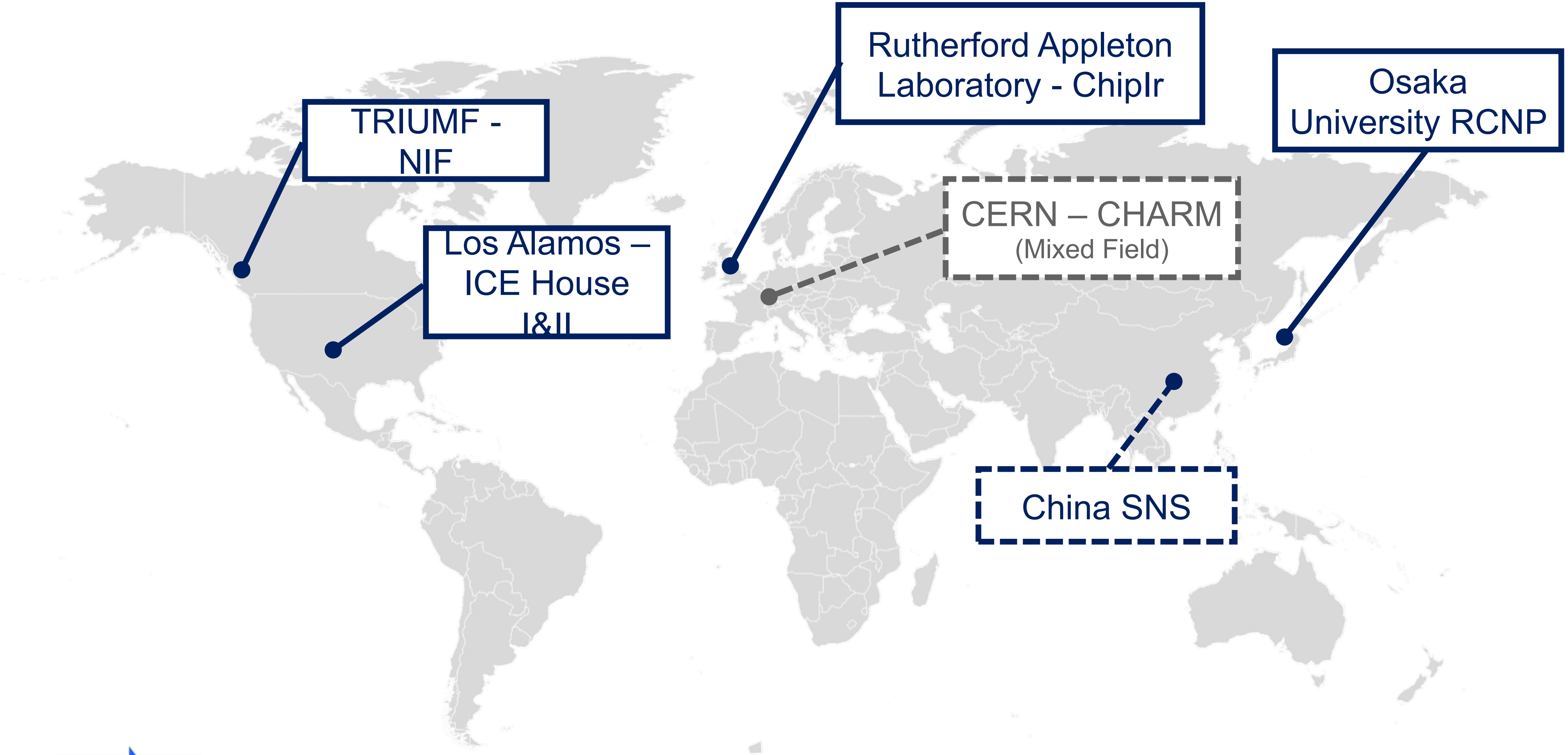
SEE Testing Facilities – Across the World



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Neutron Facilities: High Energy (>400MeV) & High Flux

Major areas of current commercial research

1. **Driverless cars** Autonomous systems
2. **Internet**: Device and system level for communication infrastructures
3. **High power devices** for renewable energy applications and automotive
4. **Aerospace** applications

Image Source: NVIDIA

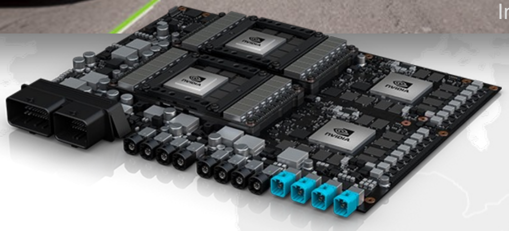

Image Source: Infineon

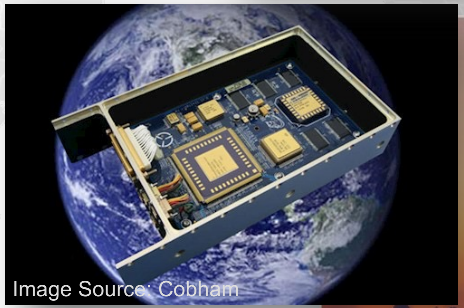

Image Source: Cobham

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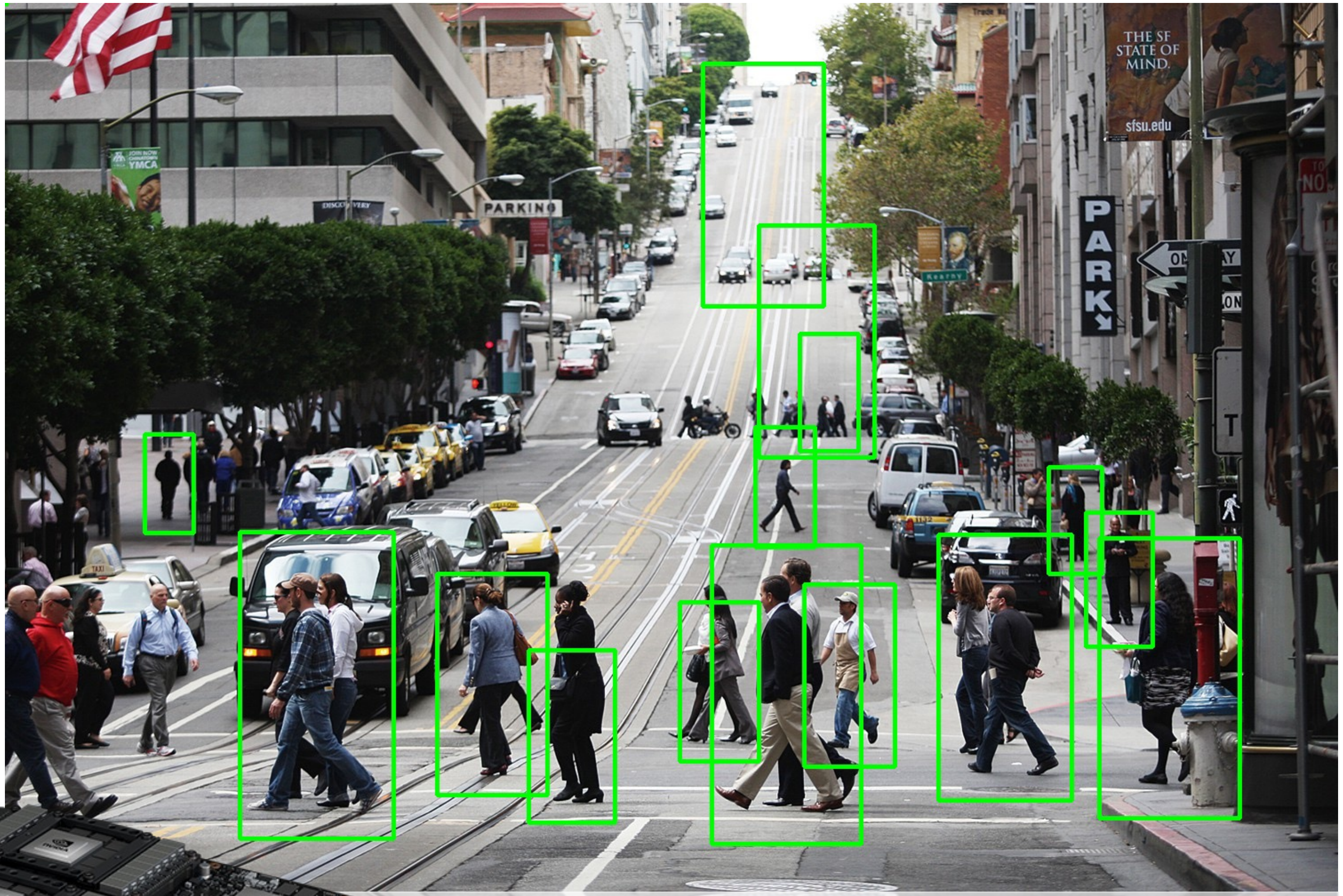
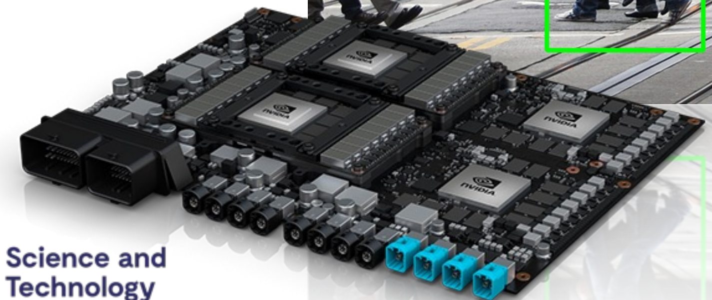
Automotive



Paolo Rech from UFRGS University, Brazil



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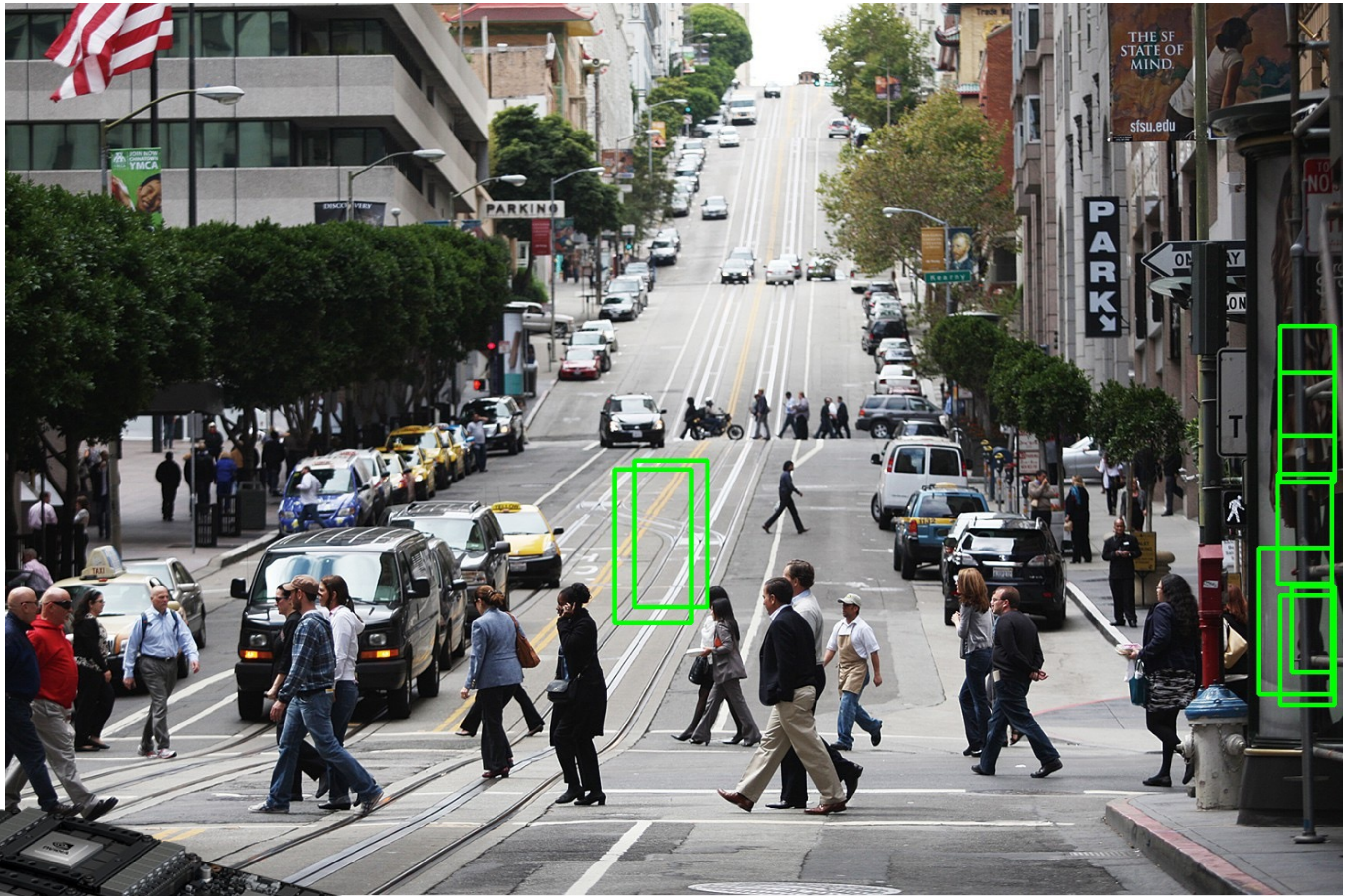

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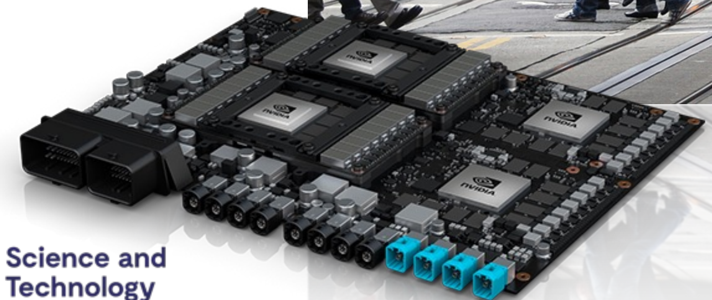

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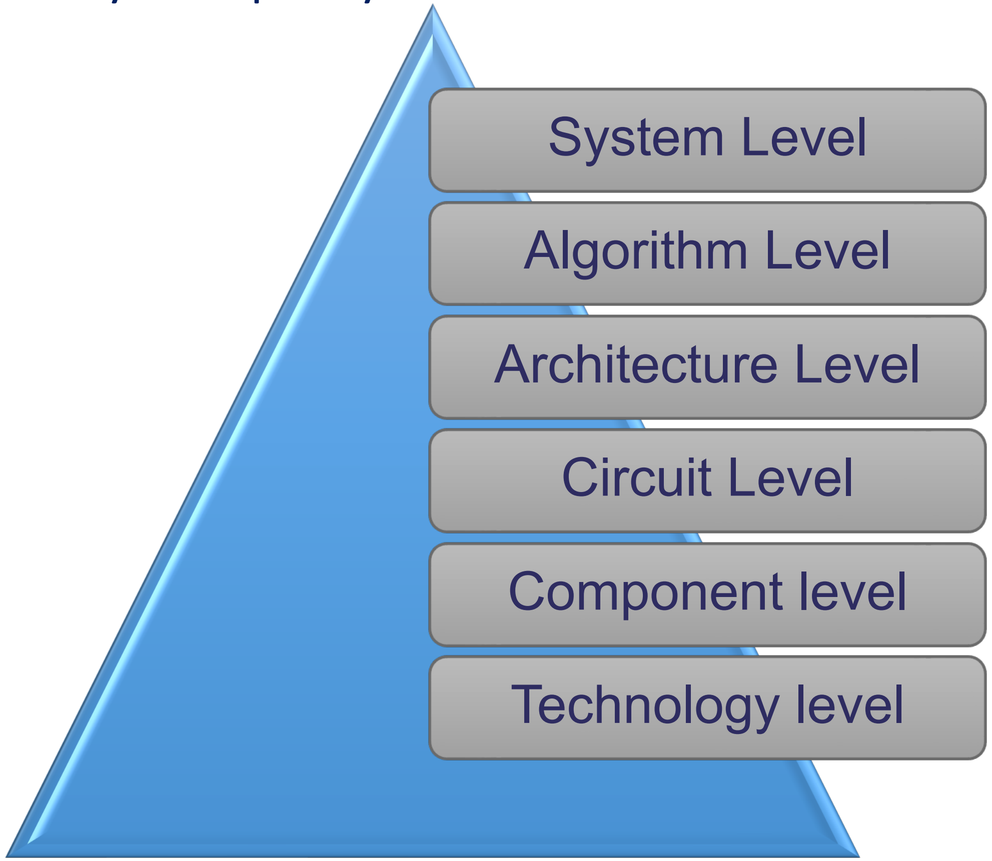
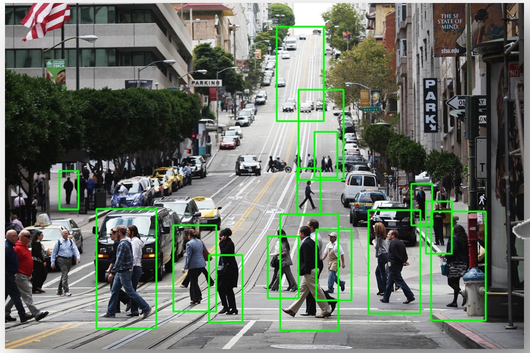
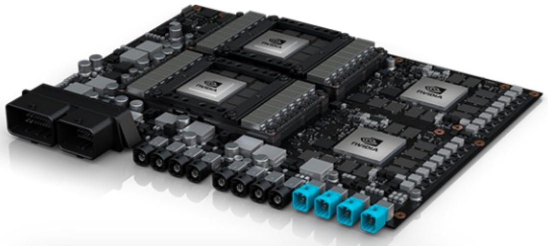
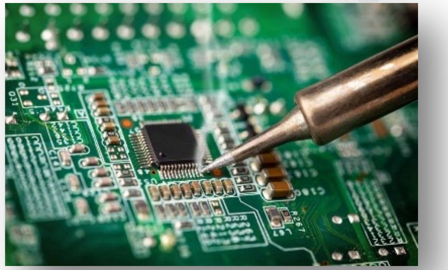
Error criticality across the stack

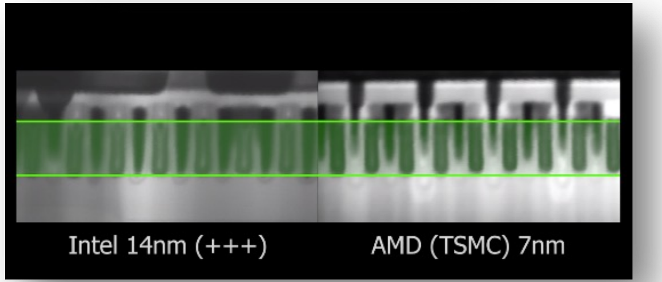
Goal: quantify and qualify











1. **Understand "critical" errors**
2. **Identify "critical" errors causes**
3. **Design efficient hardening solutions**

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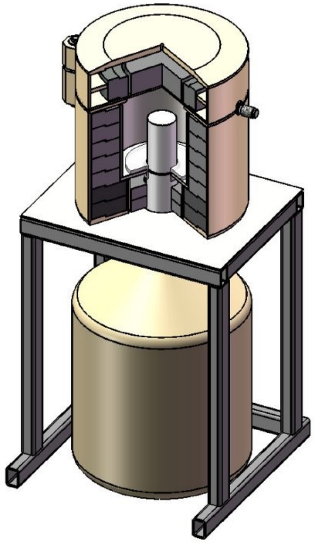
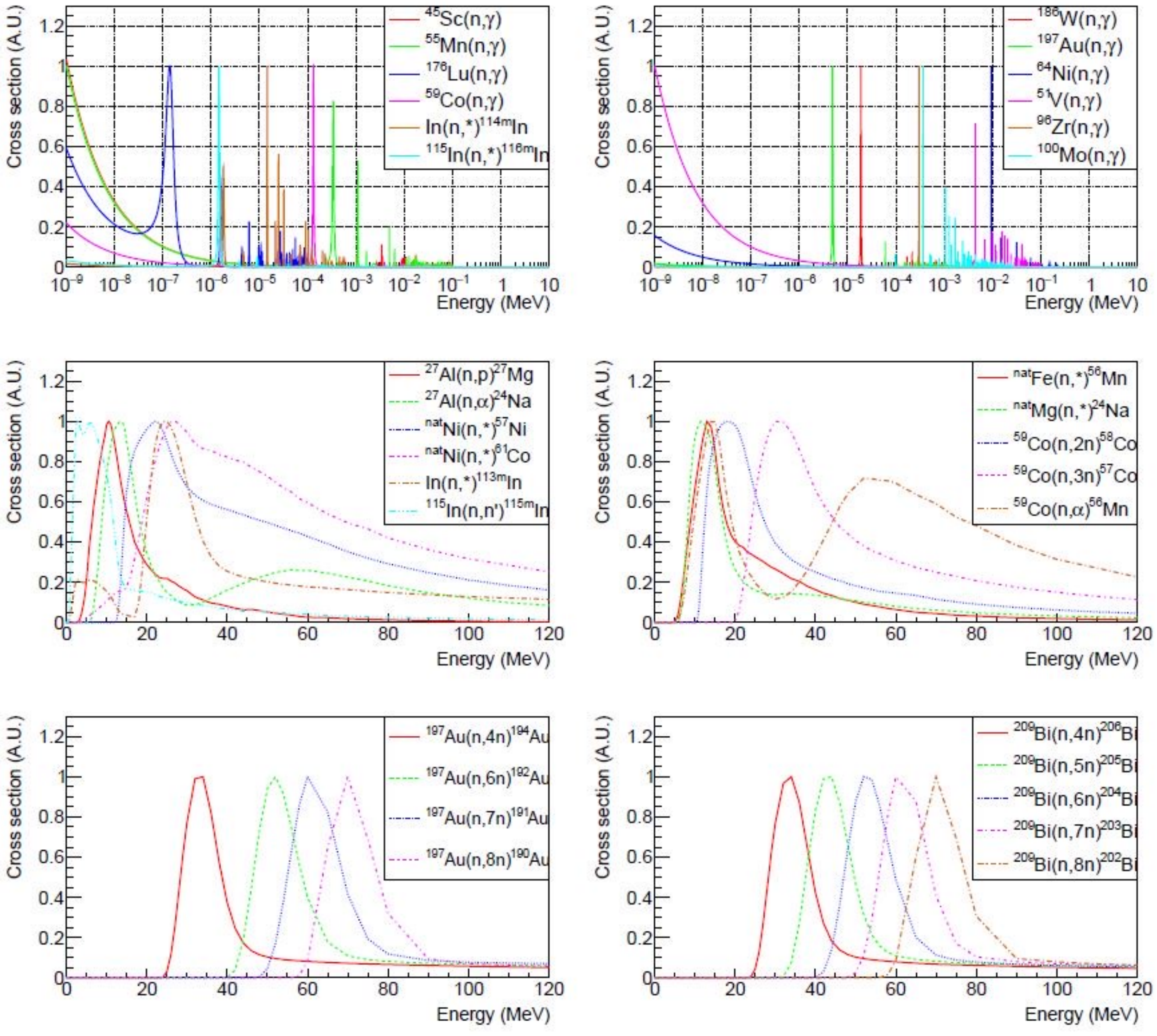
Characterization with activation foils



Targets measured on a Germanium detector



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Reaction to cover the full energy range

Unfolding with statistical approach

- Samples containing known amount of elements are irradiated and radioactive isotopes are produced by neutron activation reactions.
- Experimental measurement of the ***Activation Rate (R).***

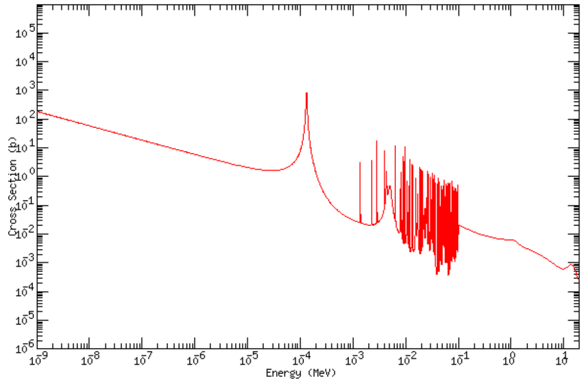
$$R = \mathcal{N} \int \sigma(E)\varphi(E)dE$$

N = number of precursor isotopes
σ(E) = activation cross section
φ(E) = neutron flux

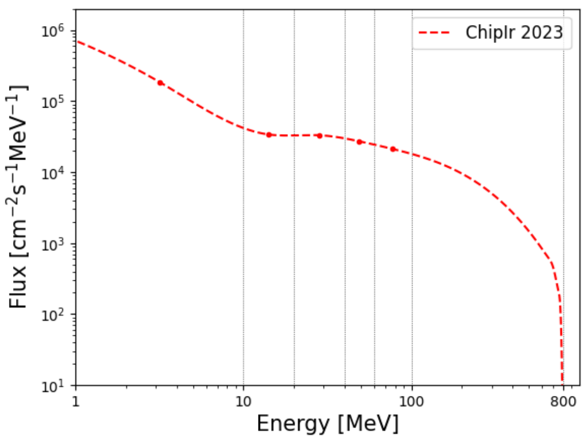
Activation Rates

Reaction	Rate (s^-1g^-1)	Uncertainty (s^-1g^-1)	Rate (s^-1g^-1)
45Sc(n,g)	1.52E+05	1.06E+04	(1.52±0.11)x10^5
51V(n,g)	2.73E+04	2.18E+03	(2.73±0.22)x10^4
55Mn(n,g)	6.56E+04	4.59E+03	(6.56±0.46)x10^4
64Ni(n,g)	8.19E+01	7.37E+00	(8.19±0.74)x10^1
96Zr(n,g)	1.35E+02	1.22E+01	(1.35±0.12)x10^2
100Mo(n,g)	2.91E+02	2.33E+01	(2.91±0.23)x10^2
115In(n,g)	5.58E+05	1.67E+04	(5.58±0.17)x10^5
176Lu(n,g)	1.60E+05	1.28E+04	(1.60±0.13)x10^5
186W(n,g)	4.13E+04	2.89E+03	(4.13±0.29)x10^4
197Au(n,g)	5.82E+05	3.49E+04	(5.82±0.35)x10^5
natMg(n,*)24Na	3.29E+03	1.65E+02	(3.29±0.16)x10^3
27Al(n,p)27Mg	2.01E+03	1.21E+02	(2.01±0.12)x10^3
27Al(n,a)24Na	2.81E+03	1.41E+02	(2.81±0.14)x10^3
natFe(n,*)56Mn	1.17E+03	7.02E+01	(1.17±0.07)x10^3
59Co(n,2n)58Co	7.41E+03	5.93E+02	(7.41±0.59)x10^3
59Co(n,3n)57Co	5.53E+03	3.87E+02	(5.53±0.39)x10^3
59Co(n,a)56Mn	1.01E+03	3.03E+01	(1.01±0.03)x10^3
natIn(n,*)113mIn	5.56E+02	2.78E+01	(5.56±0.28)x10^2
115In(n,n')115mIn	2.71E+03	1.08E+02	(2.71±0.11)x10^3
197Au(n,4n)194Au	2.56E+03	1.28E+02	(2.56±0.13)x10^3
197Au(n,6n)192Au	1.76E+03	1.06E+02	(1.76±0.11)x10^3
197Au(n,7n)191Au	1.39E+03	9.73E+01	(1.39±0.10)x10^3
197Au(n,8n)190Au	9.22E+02	5.53E+01	(9.22±0.55)x10^2
209Bi(n,4n)206Bi	2.51E+03	1.51E+02	(2.51±0.15)x10^3
209Bi(n,5n)205Bi	2.36E+03	1.65E+02	(2.36±0.17)x10^3
209Bi(n,6n)204Bi	1.68E+03	1.18E+02	(1.68±0.12)x10^3
209Bi(n,7n)203Bi	1.37E+03	9.59E+01	(1.37±0.10)x10^3
209Bi(n,8n)202Bi	1.22E+03	8.54E+01	(1.22±0.09)x10^3

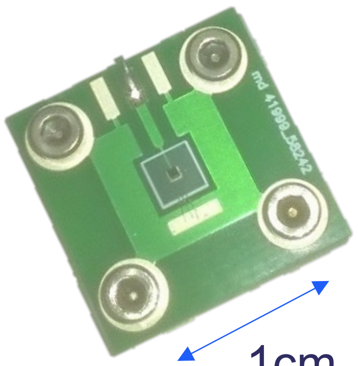
cross sections

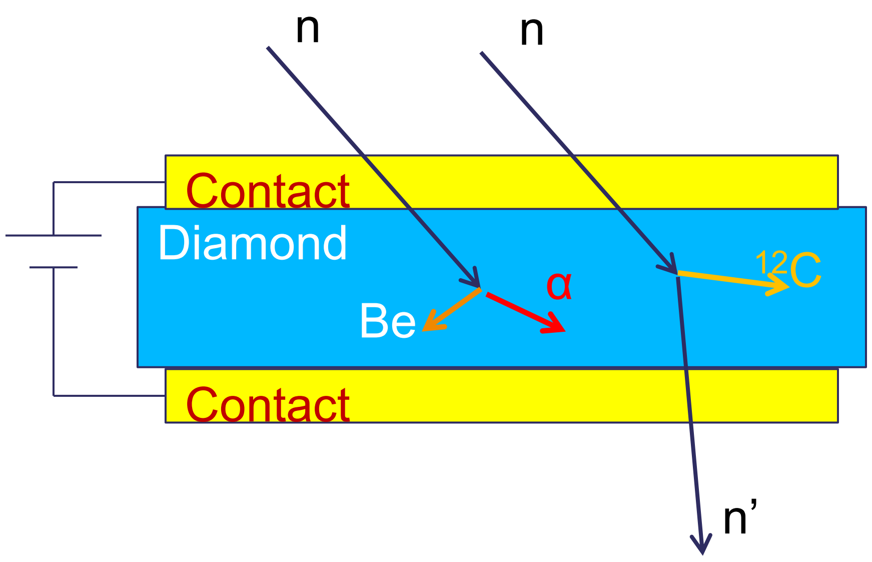


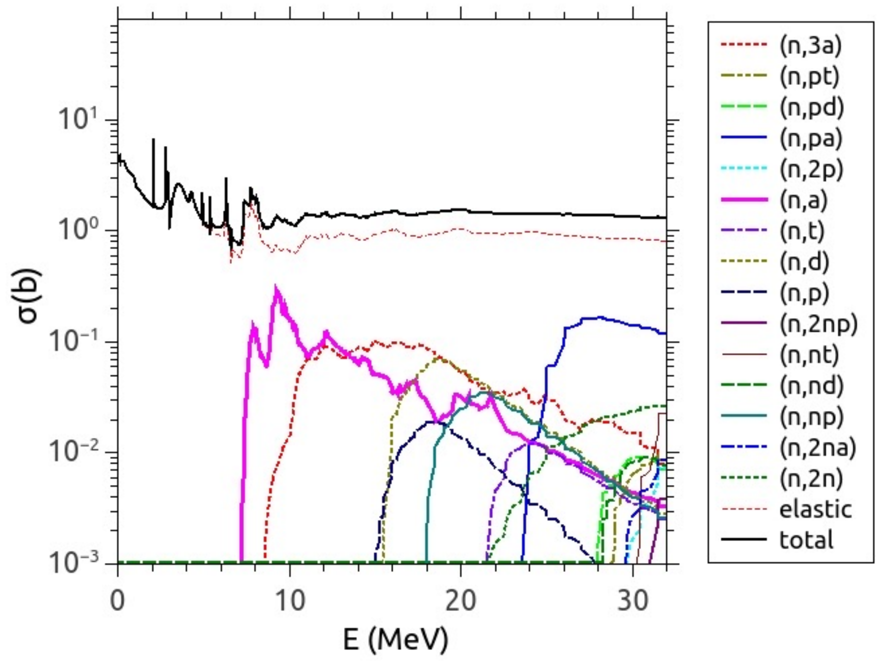
Neutron Flux



Single crystal Diamond Detectors







Carbon Cross Sections

- Radiation hardness.
- High mobility of free charges (→fast response, comparable to Si, Ge).
- Good energy resolution on deposited energy
- Room temperature operation (E_g=5.5 eV)→ No Cooling.
- Compact volume solid state detector.

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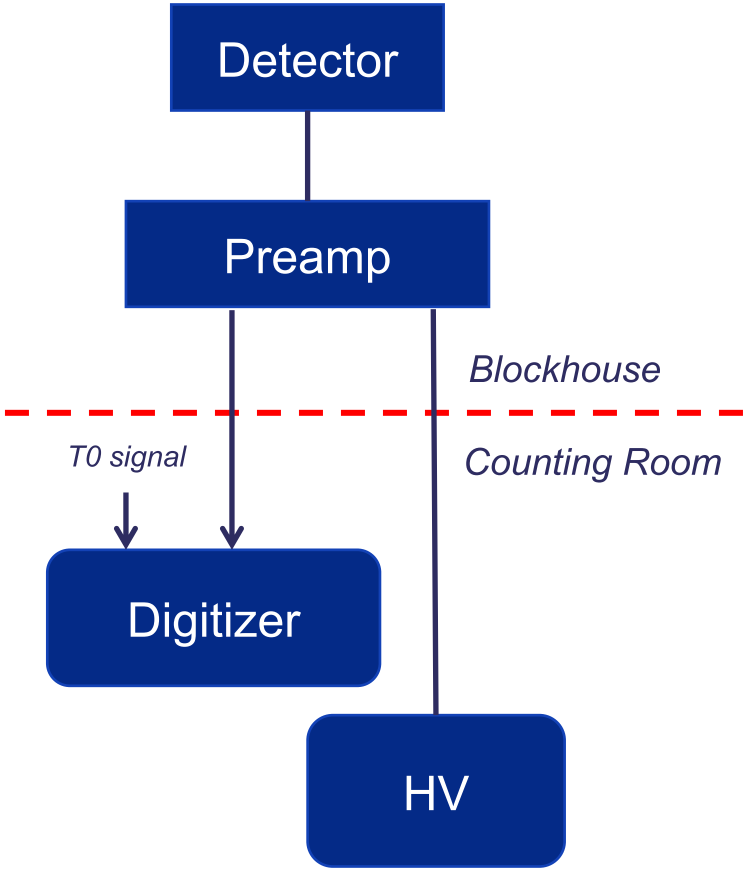
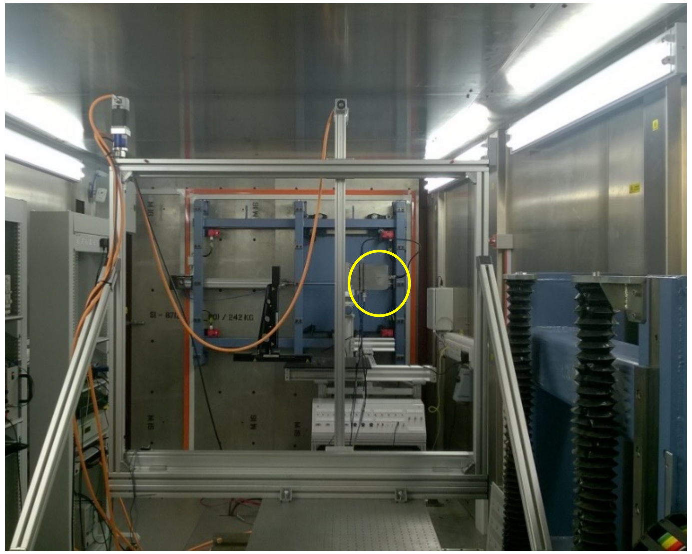
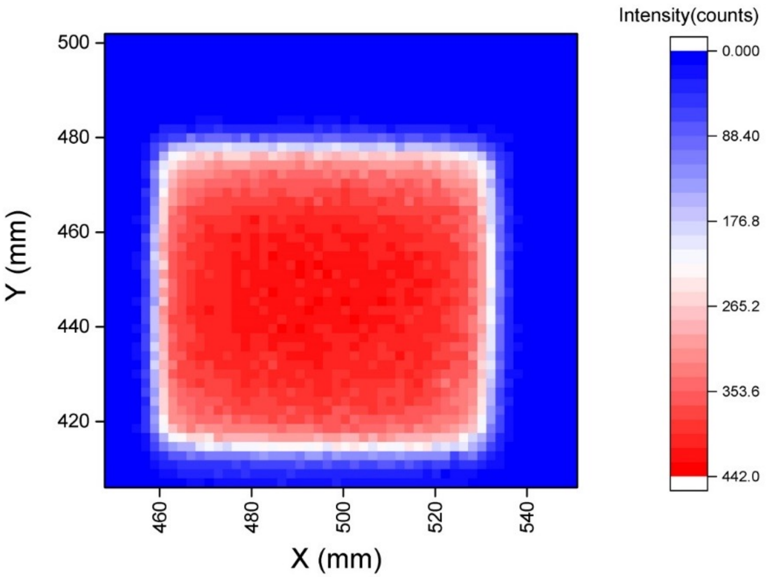
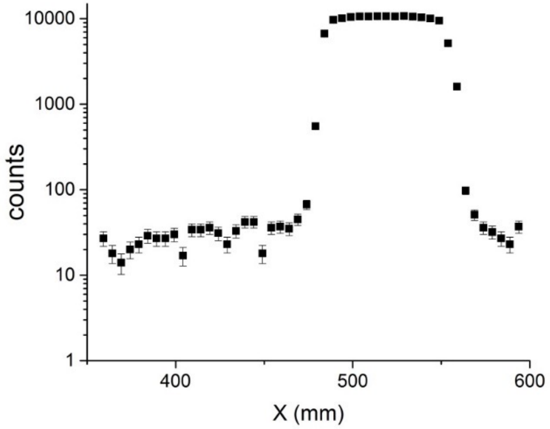
Beam profiles

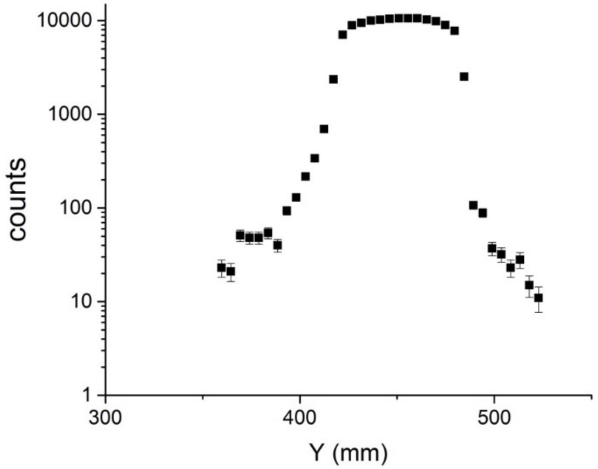






Map is measured with a diamond detector with 2 mm accuracy





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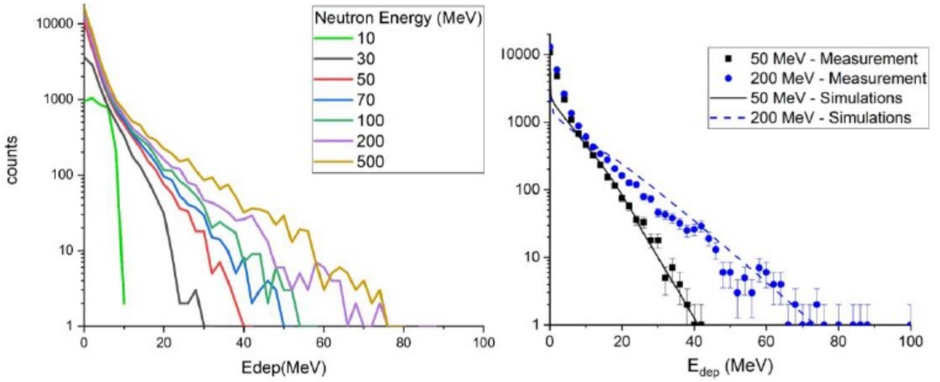
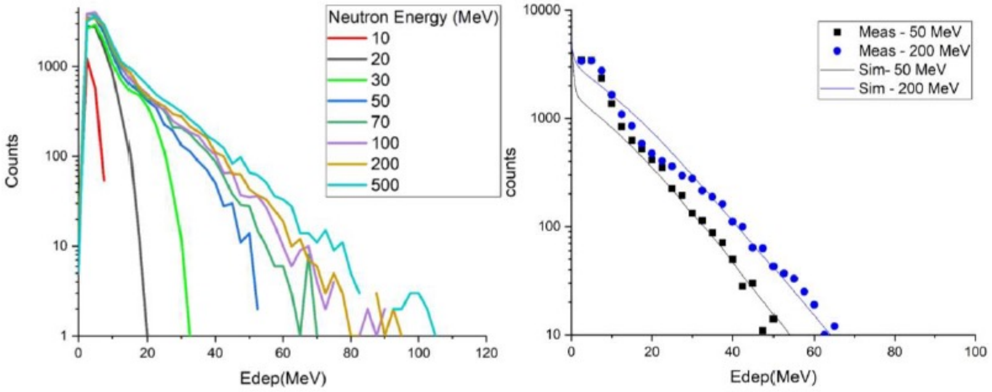
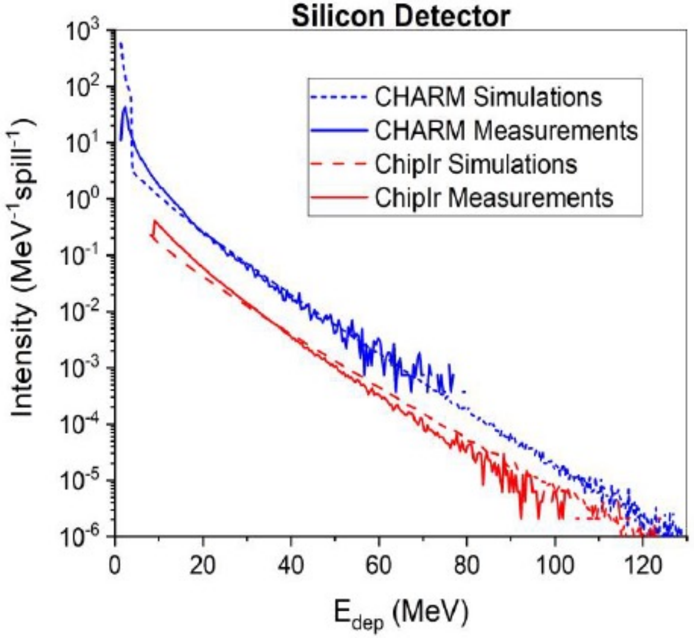
Study of deposited energy

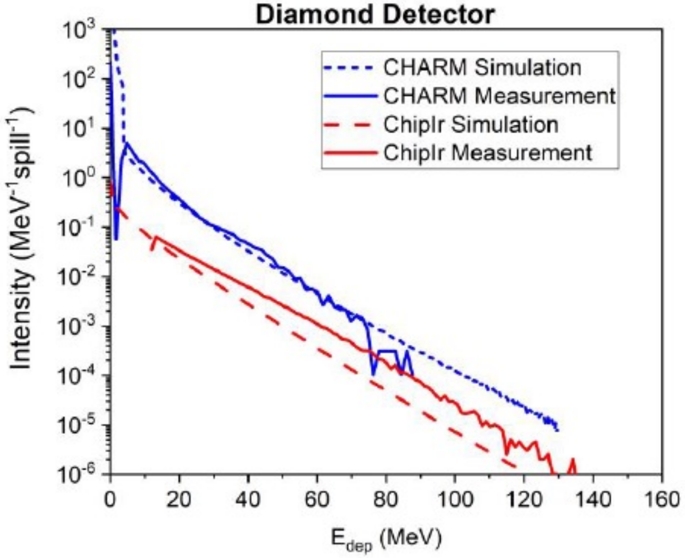
Silicon detector



Diamond detector







Data measured at nToF at CERN

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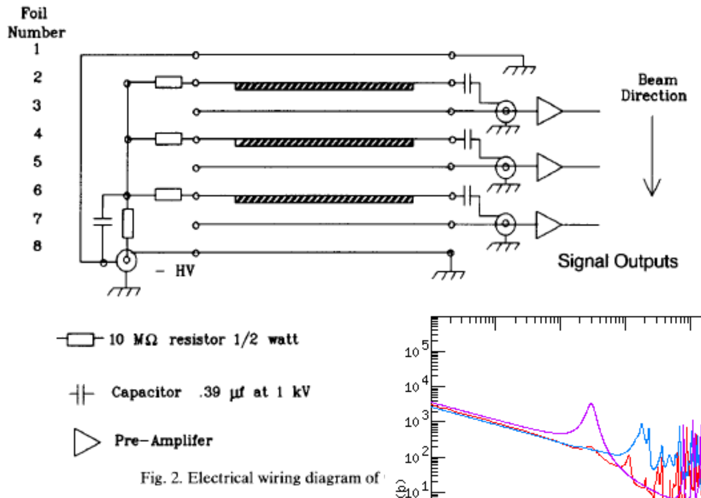
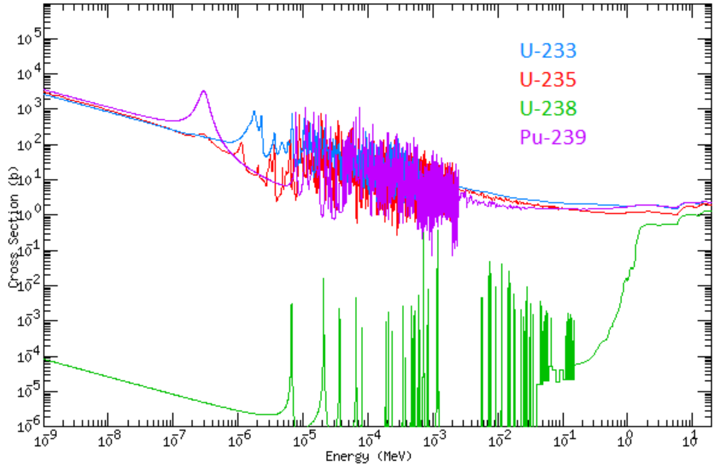
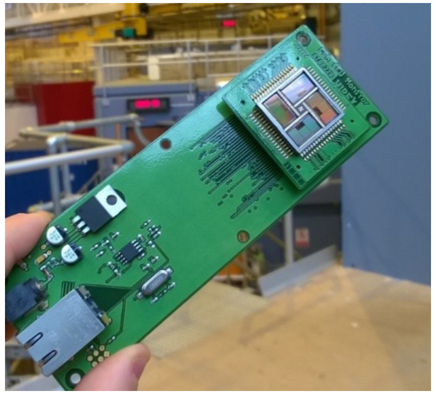
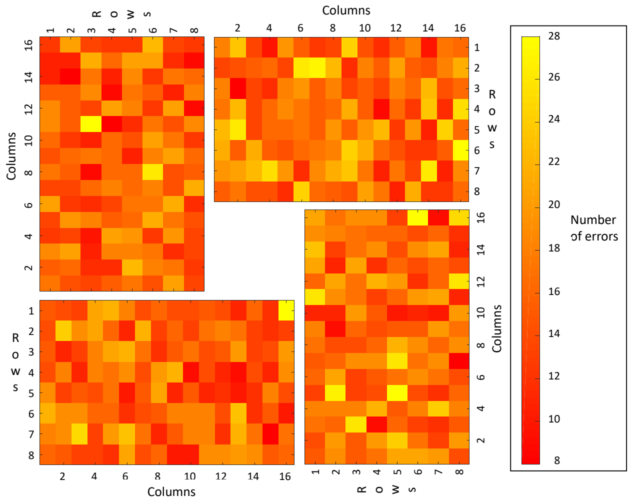
Other fast neutron detectors





Fission Chambers with ^{238}U





SRAM based detectors: bit flips

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How to select the right neutron detector?

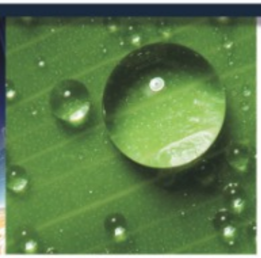
Many things to consider and find the optimal…

- **Energy range**
- **Efficiency**
- **Energy resolution / spectroscopy capabilities**
- **Gamma discrimination**
- **Time resolution**
- **Count rate capability**
- **Area / cost**

Conclusions

A world of **knowledge**

Neutron scattering research impacts on much of modern life…



… from clean energy and the environment, pharmaceuticals and health care, through to nanotechnology, materials engineering and IT.

The unique information that the technique provides is essential in making progress in contemporary materials science and in trying to solve some of the major global challenges of our time.

Energy

Energy created from burning fossil fuels has underpinned the major industrialisation of the modern world over the last 200 years. As we become more concerned with climate change and the security of our energy supply, the desire to harness other forms of energy from solar, wind, wave, hydrogen and nuclear becomes more pressing.

Hydrogen is one of the most promising fuels for the future. Research programmes to discover lightweight materials that can efficiently and safely store and transport hydrogen rely heavily on neutron scattering.

Flexible solar cells based on plastics instead of silicon offer the potential to cheaply cover wide areas of land and harness the abundant energy from the sun.

Engineering studies of components from nuclear power stations allow operating lifetimes to be confidently extended.

SEE PAGE 4

Environment and climate

In recent times, we have become acutely aware of the value of a clean and safe environment for healthy living, and the sensitivity of the climate to activity on Earth.

Neutron scattering is being used to help scientists understand the impact of pollution, work towards solutions for reducing or removing carbon dioxide from the atmosphere and industrial processes, and make more efficient use of natural resources.

Taking a molecular view of the world allows the motor industry to design lubricants and fuel additives that are kinder to the environment and to use lightweight alloys to improve fuel efficiency.

SEE PAGE 6

Medicine and health

Bioactive glass, artificial hips and gels for use in cleft palate surgery have all benefited from knowledge gained from neutron scattering. Multi-disciplinary teams of medics, physicists, materials scientists, chemists and engineers come together at research centres like ISIS and the ILL to make key breakthroughs in using materials in medicine.

The ability of neutron scattering to accurately determine molecular structures allows the behaviour of proteins, enzymes and cell membranes to be understood. Interactions of pharmaceuticals with biological molecules can be studied and compared with computer simulations, improving the chances of finding drugs to treat life-changing conditions such as Alzheimer's.

SEE PAGE 8

Electronics and IT

Over the past 50 years, the amount of information stored and processed has witnessed explosive growth, allowing hundreds of gigabytes of songs, pictures and words to be recorded onto devices which are continually shrinking in size.

The unique ability of neutron scattering to map out magnetism at the atomic scale is being used to pack more gigabytes into smaller areas, create ultra-sensitive sensors to read back the data, and develop new types of computer memory.

Studies of ceramic processing have improved the performance of mobile phone components, and testing semiconductor chips to determine the effects of cosmic ray neutrons is allowing companies to confirm the performance of their electronic systems.

SEE PAGE 10

Manufacturing and industry

Millions of tonnes of materials are processed every day across the planet to manufacture the huge range of products that we need for daily life, from soaps, cosmetics and drugs through to cars, planes and industrial solvents. A small amount of molecular knowledge from neutron scattering experiments can go a long way in improving the efficiency, quality and price of industrial products.

Unique information from experiments at the ILL and ISIS is used daily in the manufacture of products used to keep people and their homes clean and fresh. Energy efficient mass production of key industrial chemicals is founded on basic knowledge of molecular interactions. Quality assurance of components in the aerospace and motor industries relies on long-term research programmes confirming the best conditions for making precision components.

SEE PAGE 12

Natural world

Our world and universe continue to fascinate, intrigue and surprise. We can learn many lessons from plants and animals on how to solve common problems and gain deeper understanding of our place in the universe by studying the geology and natural processes of the planets.

Neutron scattering is being used to tease the secrets of spinning silk from spiders and how lizards avoid freezing in winter. Understanding how plants can defend themselves against disease offers new potential for crop breeding and medicines.

Replicating the extreme conditions found in the deep earth or the planets of the Solar System is bringing new insight to planetary science. Neutron beams can penetrate through the heavy engineering equipment used to generate high pressures to measure the properties of rocks and fluids needed for computer modelling.

SEE PAGE 14

Heritage science

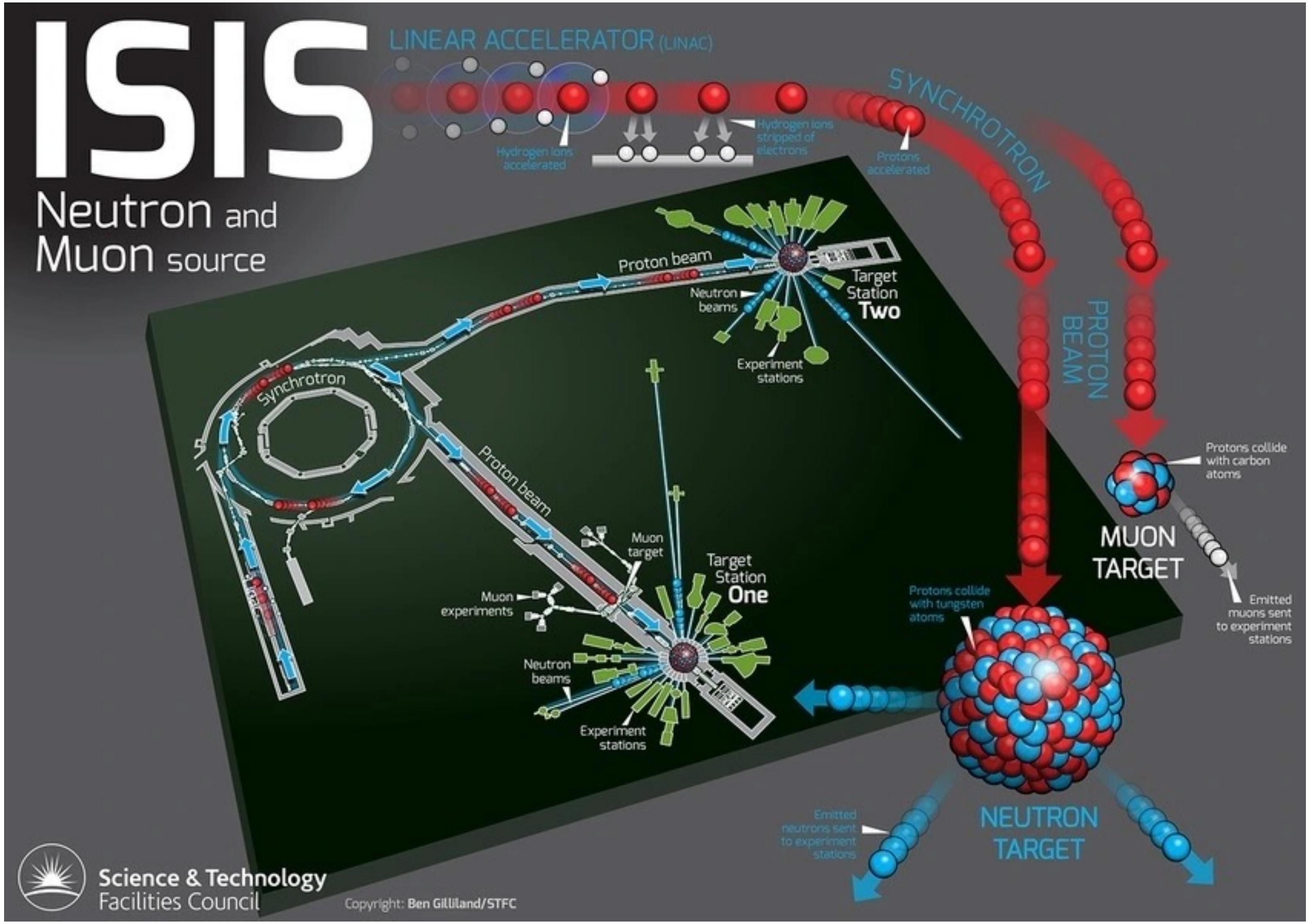
The origins and history of objects from museums and archaeological sites can be safely investigated using neutron scattering without damaging them or affecting their value.

Civil engineering projects rely on archaeologists to assess the significance of ancient remains that will be disturbed. Neutron scattering has been used to examine Roman objects found under the A2 in Kent which have similarities to those found at Pompeii.

Museums across Europe are using neutron techniques to understand how ancient Japanese swords were made during the 14th to 17th centuries.

Fresh thinking about the Battle of Towton is coming from neutron scattering experiments of battlefield weapons. Fought near Tadcaster in Yorkshire in 1461, it was the most dramatic battle of the Wars of the Roses.

SEE PAGE 16



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Thanks!

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